PB81-122202

Second Symposium of the Transfer and Utilization of Particulate Control Technology: Volume I Control of Emissions from Coal Fired Boilers

Denver Research Inst., CO

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Sep 80

U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

EPA-600/9-80-039a
September 1980

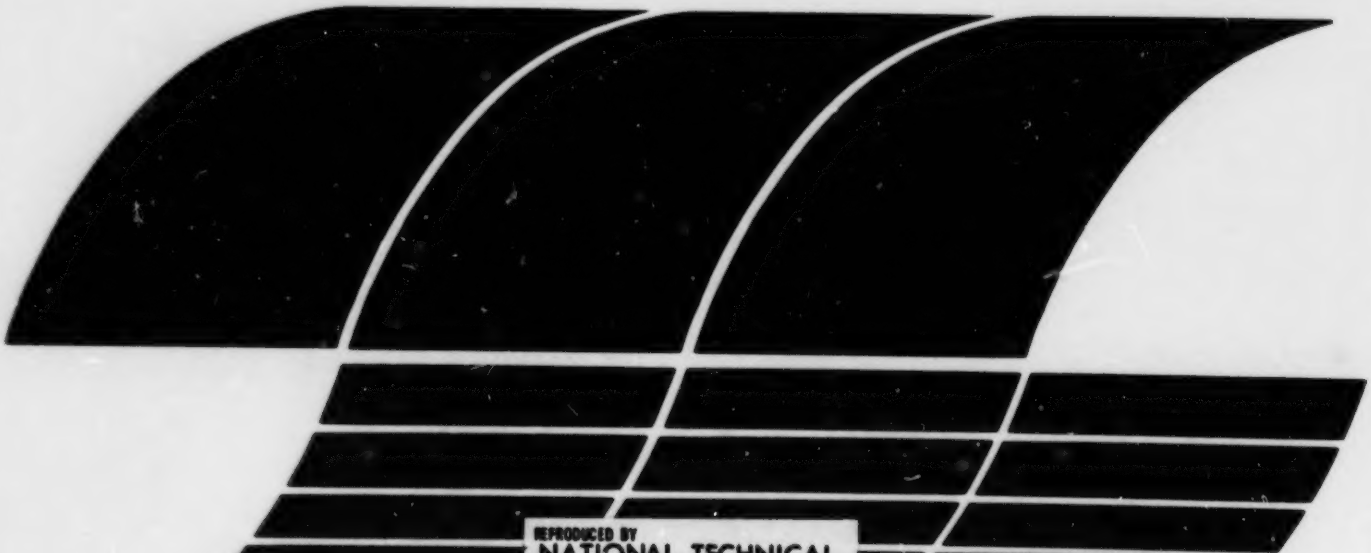
Research and Development

PB81-122202

EPA

Second Symposium on the Transfer and Utilization of Particulate Control Technology

Volume I.
Control of Emissions from Coal Fired Boilers



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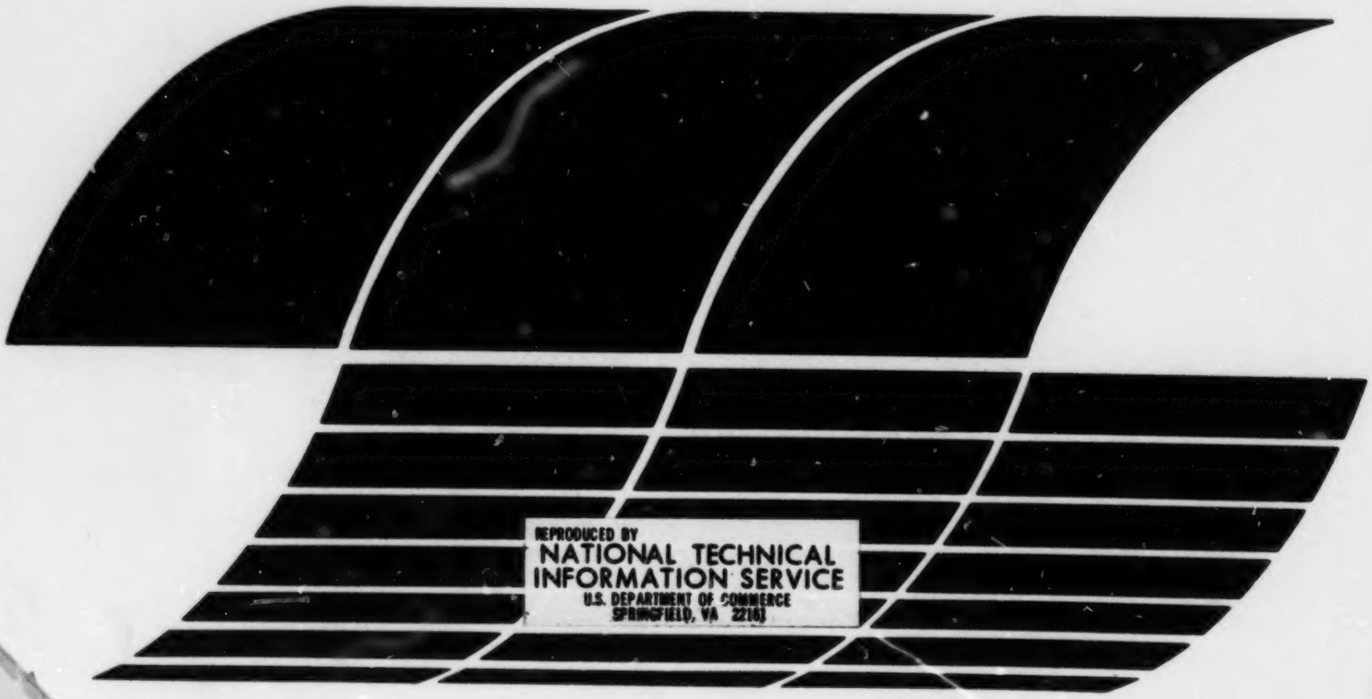

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/9-80-039a

2.
IERL-RTP-1061

3. RECIPIENT'S ACCESSION NO.
PB81 122202

4. TITLE AND SUBTITLE
Second Symposium on the Transfer and Utilization of
Particulate Control Technology (Denver, July 1979)
Volume I. Control of Emissions from Coal Fired Boilers

5. REPORT DATE
Sept. 1980 issuing date.

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
F.P. Venditti, J.A. Armstrong and Michael Durham

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Denver Research Institute
P.O. Box 10127
Denver, Colorado 80210

10. PROGRAM ELEMENT NO.
EHE624

11. CONTRACT/GRANT NO.
R805725

12. SPONSORING AGENCY NAME AND ADDRESS
Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED
Proceedings; 6/79-6/80

14. SPONSORING AGENCY CODE
EPA/600/13

15. SUPPLEMENTARY NOTES
IERL-RTP project officer is Dennis C. Drehmel, MD-61, 919/541-2925. EPA-600/7-79-044a thru-044d are proceedings of the 1978 symposium.

16. ABSTRACT

The proceedings document the approximately 120 presentations at the EPA/IERL-RTP-sponsored symposium, attended by nearly 800 representatives of a wide variety of companies (including 17 utilities). The keynote speech for the 4-day meeting was by EPA's Frank Princiotta. The meeting included a plenary session on enforcement. Attendees were polled to determine interest areas: most (488) were interested in operation and maintenance, but electrostatic precipitators (ESPs) and fabric filters were a close second (422 and 418, respectively). Particulate scrubber interest appears to be waning (288). Major activities of attendees were: users, 158; manufacturers, 184; and R and D, 182. Technical presentations drawing great interest were the application of ESPs and baghouses to power plants and the development of novel ESPs. As important alternatives to ESPs, baghouses were shown to have had general success in controlling coal-fired power plant emissions. When operating properly, baghouses can limit emissions to <5 mg/cu nm at pressure drops of <2 kPa. Not all baghouse installations have been completely successful. Both high pressure drop and bag loss have occurred (at the Harrington Station), but these problems appear to be solved.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Dust Aerosols Electrostatic Precipitators Filters Fabrics Scrubbers Flue Gases	Pollution Control Stationary Sources Particulate Baghouses	13B 11G 07D 13I 14G 11E 07A 21B

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS *(This Report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES
639

22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

☆ U.S. GOVERNMENT PRINTING OFFICE: 1980--657-165/0157

EPA-600/9-80-039a
September 1980

SECOND SYMPOSIUM ON THE TRANSFER AND UTILIZATION OF PARTICULATE CONTROL TECHNOLOGY
VOLUME I. CONTROL OF EMISSIONS FROM COAL FIRED BOILERS

by

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Grant Number: R805725

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RESEARCH TRIANGLE PARK, NC 27711

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ABSTRACT

The papers in these four volumes of Proceedings were presented at the Second Symposium on the Transfer and Utilization of Particulate Control Technology held in Denver, Colorado during 23 July through 27 July 1979, sponsored by the Particulate Technology Branch of the Industrial Environmental Research Laboratory of the Environmental Protection Agency and hosted by the Denver Research Institute of the University of Denver.

The purpose of the symposium was to bring together researchers, manufacturers, users, government agencies, educators and students to discuss new technology and to provide an effective means for the transfer of this technology out of the laboratories and into the hands of the users.

The three major categories of control technologies - electrostatic precipitators, scrubbers, and fabric filters - were the major concern of the symposium. These technologies were discussed from the perspectives of economics; new technical advancements in science and engineering; and applications. Several papers dealt with combinations of devices and technologies, leading to a concept of using a systems approach to particulate control rather than device control. Additional topic areas included novel control devices, high temperature/high pressure applications, fugitive emissions, and measurement techniques.

These proceedings are divided into four volumes, each volume containing a set of related session topics to provide easy access to a unified technology area.

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RM-064-EPA-79/R1

COST AND PERFORMANCE OF PARTICULATE CONTROL DEVICES FOR LOW-SULFUR WESTERN COALS

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ABSTRACT

A computer model is being developed and used to assess the cost and performance of hot-side and cold-side electrostatic precipitators (ESPs), fabric filters, and venturi scrubbers for particulate control on low-sulfur western coals. The model's performance module incorporates simplified versions of the EPA/Southern Research Institute ESP model, the EPA/Air Pollution Technology, Inc., venturi model, and the EPA/GCA, Inc., fabric filter model. It calculates the control-device size required to meet a specified emission limit for any size of unit burning a specified coal. The cost modules developed for each of the particulate control devices are used to select the device having the lowest levelized cost. The program is structured to allow the use of an ESP and a venturi scrubber in series and calculates the least-cost combination of these devices. In this paper the model is discussed and selected results of the assessment are presented.

COST AND PERFORMANCE OF PARTICULATE CONTROL DEVICES FOR LOW-SULFUR WESTERN COALS

INTRODUCTION

Teknekron Research, Inc., is developing a Particulate Control Performance and Cost Model (PC2M) for use in the design and evaluation of particulate control devices for coal-fired boilers burning low-sulfur coal. The PC2M uses state-of-the-art ESP, venturi, and fabric filter performance models for the design of particulate control devices and detailed cost models to calculate capital and operating costs. This model brings together for the first time simplified versions of the EPA/SoRI ESP model, the EPA/APT venturi model, and the EPA/GCA fabric filter model in a format that allows the design of the particulate control device to meet a specified emission limit at the lowest levelized cost. In addition, the PC2M is structured to model the performance of a cold-side ESP in series with a venturi scrubber.

The model is being developed on the CDC 7600 computer at the Lawrence Berkeley Laboratory and is scheduled for completion in August 1979. The final report and user's guide will be available by the end of the year.

In the following sections the overall modeling approach and the individual performance and cost models are discussed. The last section presents a typical case study in which the PC2M was used to calculate particulate control costs for a new 500-MW boiler.

OVERALL MODELING APPROACH

A schematic representation of the PC2M is provided in Figure 1. Inputs to the computer model include boiler characteristics, coal properties, environmental regulations, and ash characteristics. If the user chooses not to provide boiler characteristics and coal properties, nominal default values are provided for these parameters, while the user must input, in a namelist format, values for the environmental regulations and ash characteristics. From these inputs the model calculates the gas flow rate, uncontrolled emissions, and the penetration (1 - removal efficiency) required to meet the stated emission limit. The PC2M then calls the appropriate performance and cost models to design and cost the various particulate control devices.

If an ESP and venturi in series is being evaluated, the PC2M successively calls the ESP and venturi models using a binomial search iteration technique until the least-cost combination is found.

DISCUSSION OF CONTROL DEVICE MODELS

Fabric Filter Performance Model

The fabric filter performance model is the one developed by GCA for EPA[1] minus the graphics capability. This model uses fabric filter design and operating data along with data on dust and fabric properties in the calculation of dust penetration. The PC2M uses the GCA model in an iterative fashion to determine the least-cost combination of pressure drop and face velocity to provide the required penetration.

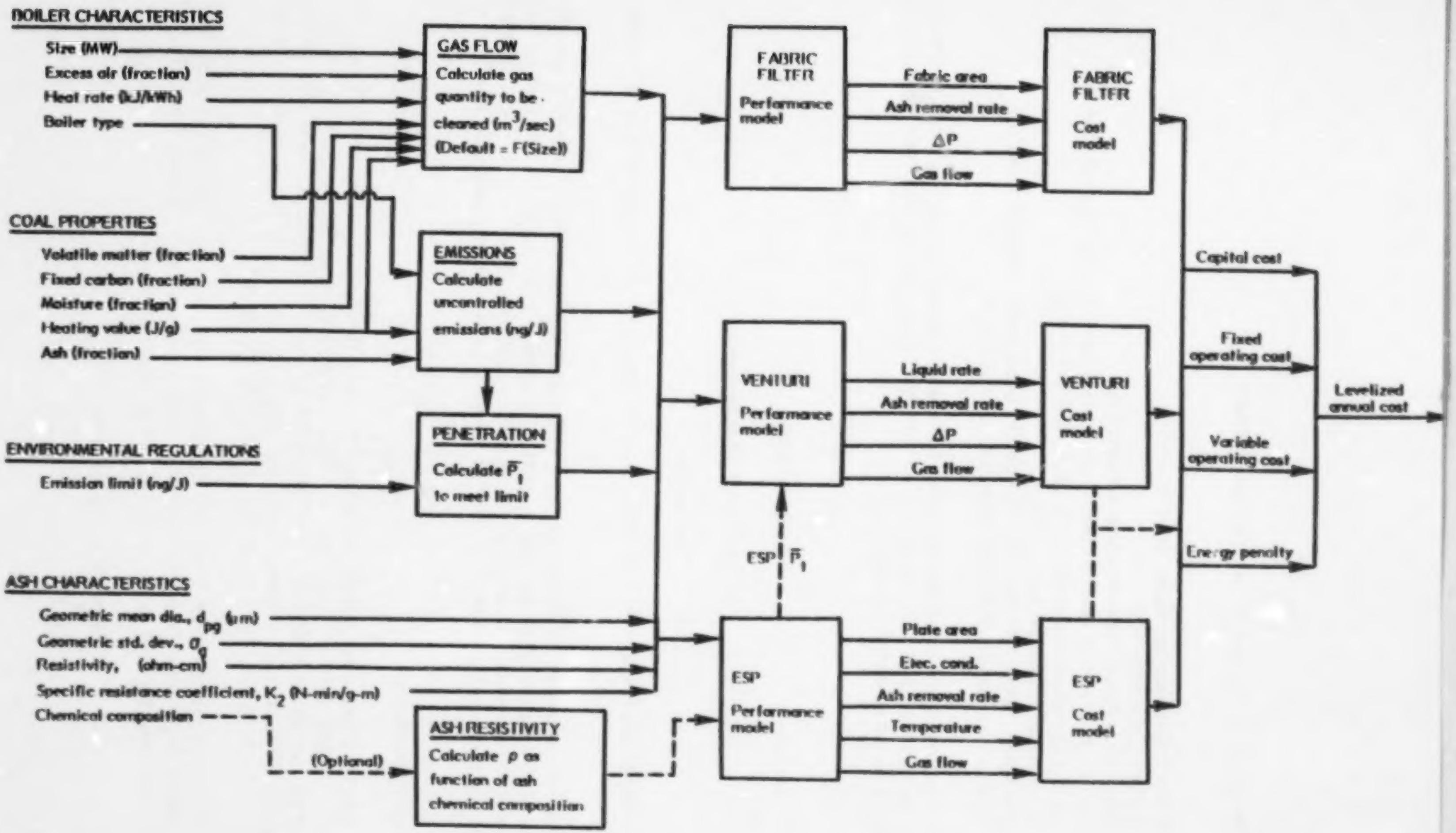

Figure 1. Particulate control performance model.

The iterative technique is summarized below:

1. Select limiting pressure drop
2. Select face velocity
3. Use GCA model to calculate penetration
4. Perform steps 2 and 3 until calculated penetration equals the required penetration within a user-defined margin
5. Calculate levelized annual cost
6. Perform steps 1 through 5 until least-cost combination of limiting pressure drop and face velocity is found

Successive values of face velocity are selected using a power curve iteration technique. This technique assumes that the relationship between penetration and face velocity can be represented by an equation of the form:

$$V = aP_t^{\,b} \tag{1}$$

where: V = face velocity

P_t = calculated penetration

$a\&b$ = constants

After each iteration, a and b are recalculated on the basis of the most recent values of V and P_t.

Successive values of limiting pressure drop are selected using a binomial search in which steps of decreasing size are taken until the lowest cost value of limiting pressure drop is found. The model may also be used in a noniterative manner to determine penetration for a given face velocity and limiting pressure drop or cleaning cycle.

Fabric Filter Cost Model

The fabric filter cost model is based on costs developed by Stearns-Roger, Inc., for EPRI.[2] Costs are a function of face velocity, gas flow rate, number of compartments, pressure drop, and the quantity of ash removed. There are 19 user-defined inputs with default values, including bag life, bag cost, labor rate, number of modules, duty factors, and time required for bag replacement.

The model assumes that bag life is a function of face velocity, with higher velocities requiring more frequent cleaning and resulting in a lower bag life. The relationship between face velocity and bag life is assumed to be:

$$\text{Bag Life} = \text{Bag L Fac}\ \frac{0.61}{V}^{\,b}\quad , \tag{2}$$

where:

Bag L Fac = Bag life in years at a face velocity of 0.61 meters per minute

V = face velocity in meters per minute

b = user-defined constant with a default value of 0.6

If the user feels that bag life is independent of face velocity, a value of b = 0 may be specified.

The user has the option of having the model perform a present worth analysis in order to provide levelized costs. User inputs required by the levelizing routine are: discount rate, fixed charge rate, economic life, and the escalation plus inflation rate.

ESP Performance Model

The ESP performance model uses the Southern Research Institute (SoRI) model as simplified by Leslie Sparks.[3] That simplified model calculates penetration as a function of ESP size and operating conditions for particles of various size. Rapping puff and small diameter migration velocity adjustments from the original SoRI model[4] are included in the PC2M ESP model. The PC2M ESP model calculates the penetration of particles in distinct size ranges between 0.01 µm and $(d_g)(\sigma_g)$ µm, where d_g is the geometric mean particle diameter and σ_g is the geometric standard deviation.

The model includes 80 tables of migration velocity as a function of particle diameter for use in calculating total penetration. These tables were developed using the SoRI ESP model and are representative of typical hot-side and American cold-side ESPs. Temperatures, specific collection areas, dust loadings, and current densities represented by these migration velocities are illustrated in Table 1. Hall's equation[5] is used to select the maximum current density allowed for a given ash resistivity. The model selects the migration velocity table that corresponds most closely to the design and operating conditions of the ESP under investigation.

A power curve iteration technique similar to the one used in the fabric filter performance model is used to find the specific collection area required to produce the desired penetration.

ESP Cost Model

The ESP cost model is based on costs developed by Stearns-Roger, Inc., for EPRI.[2] Costs are a function of ESP type (hot-side or American cold-side), collector area, gas flow rate, electrical conditions in the ESP, and the quantity of ash removed. There are 11 user-defined inputs with default values; included, for example, are duty factors, capacity factor, load factors, fan and motor efficiencies, contingency costs, and the cost of electricity.

TABLE I. ESP DESIGN AND OPERATING CONDITIONS FOR WHICH MIGRATION VELOCITIES ARE AVAILABLE

Case Number		1	2	3	4	5	6	7	8
SCA ($m^2/m^3/sec$)		49.2	157.4	49.2	157.4	29.1	118.0	29.1	118.0
Dust load (g/m^3)		4.58	4.58	11.44	11.44	3.43	3.43	8.01	8.01
Temperature (^oC)		150	150	150	150	370	370	370	370
Current Density (nA/cm^2)	Resitivity (ohm-cm)								
70	1.0E10					x	x	x	x
57	1.5E10					x	x	x	x
50	1.7E10	x	x	x	x				
42.9	2.0E10	x	x	x	x	x	x	x	x
28.7	3.0E10					x	x	x	x
21.6	4.0E10	x	x	x	x	x	x	x	x
17.3	5.0E10	x	x	x	x	x	x	x	x
11.6	7.5E10					x	x	x	x
8.7	1.0E11	x	x	x	x	x	x	x	x
5.8	1.5E11					x	x	x	x
4.4	2.0E11	x	x	x	x	x	x	x	x
2.2	4.0E11	x	x	x	x				
1.7	5.0E11	x	x	x	x				
0.9	1.0E12	x	x	x	x				
0.45	2.0E12	x	x	x	x				

The cost of electricity to energize the ESP is calculated from the collector area, operating voltage, and current density.

As with the fabric filter costs, the user has the option of having the costs reported on a levelized basis.

Venturi Performance Model

The venturi performance model is the EPA/APT performance model modified by Sparks[3] for use on a programmable calculator. The model calculates penetration as a function of particle size for specified operating conditions of throat velocity and liquid-to-gas ratio. Particles in distinct size ranges between 0.01 µm and (d_g) (σ_g) µm are included in the penetration calculations.

The PC2M uses the venturi performance model iteratively to find the lowest pressure drop combination of throat velocity and liquid-to-gas ratio that achieves the required penetration. A power curve iteration technique is used to find the required throat velocity at a given liquid-to-gas ratio, while a binomial search is used to iterate over liquid-to-gas-ratio values. This iterative technique is the same as that used in the fabric filter performance model, with venturi throat velocity replacing fabric filter face velocity and liquid-to-gas ratio replacing limiting pressure drop.

If the user wishes to calculate venturi penetration for a given set of operating conditions, two of the three following operating parameters must be supplied: pressure drop, throat velocity, liquid-to-gas ratio.

Venturi Cost Model

The venturi cost model is based on cost information contained in reports by Ponder et al.[6] and Kinkley and Neveril.[7] Costs are calculated as a function of gas flow rate, liquid-to-gas ratio, pressure drop, number of modules, and whether or not an FGD system is included for SO_2 control. If FGD is included, a common pond is used for ash and sludge disposal, and the cost of flue gas reheat is assigned to the FGD system.

The cost model includes 10 user-defined inputs with default values. Typical user-defined inputs include: number of spare modules, water cost, steam cost, electricity cost, and fan and pump efficiencies.

Capital and operating costs can be reported either on a first-year annualized basis or on a levelized basis over the life of the system.

CASE STUDY

Presented here are the results of a typical case study comparing the costs of various control devices designed to meet a particular emission limit. Since the fabric filter performance model is not yet fully implemented in the PC2M, curves presented by Dennis et al.[8] were used to find various combinations of the face velocity and limiting pressure drop needed for the required penetration. The corresponding average pressure drop and face velocity were then used in the PC2M fabric filter cost model to calculate the fabric filter costs.

Fabric filter performance was determined for a system with the following dust and fabric properties:

- Inlet particulate concentration, $c_i = 6.87$ g/m^3
- Specific cake resistance, $K_2^* = 1.0$ N-min/g-m
- Effective drag, $S_E^{**} = 400$ N-min/m^3
- Residual fabric loading, $W_R = 50$ g/m^3
- Fractional area cleaned, $a_c = 0.40$

The following model input parameters were used in the case study:

Boiler Characteristics

New 500-MW dry-bottom pulverized coal unit
Capacity factor = 0.65

Coal Properties

23,258 J/g (10,000 Btu/lb)
10% ash

Environmental Regulations

Particulate limit = 13 ng/J (0.03 lb/MBtu)

Ash Characteristics

$d_g = 20\ \mu m$
$\sigma_g = 4\ \mu m$

Economic Factors

January 1979 costs and dollars
Electricity cost = 40 mills/kWh
Discount rate = 16.1%
Fixed charge rate = 19.2%
Escalation rate = 5.5%/yr
Economic life = 30 yrs

For this combination of ash properties and environmental regulations, a 99.65 percent collection efficiency is required if 85 percent of the coal ash leaves the boiler as fly ash.

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* at a face velocity of 0.61 m/min and 25°C

** at 25°C

Levelized fabric filter costs are presented in Figure 2 as a function of average fabric pressure drop (corresponding to various face velocities) for bag lives of between 0.5 and 4 years. In all cases a fabric filter operating at a face velocity of 1.0 meter per minute was found to be the design of lowest cost. The least-cost design point may indeed be somewhere between 0.61 and 1.0 meters per minute. However, the curves used for the performance analysis did not allow for the evaluation of devices operating in this range of face velocities.

Levelized hot-side EPS costs are presented in Figure 3 as a function of ash resistivity. The flat portion of the curve reflects the effect of limiting hot-side current densities to 70 nA/cm^2.

Figure 4 shows the levelized costs of a cold-side ESP, a venturi scrubber (with and without FGD), and various combinations of these devices. Cold-side ESP costs are plotted on the left-hand side of the figure for various ash resistivities, while venturi costs are plotted on the right-hand side. The curves represent various combinations of ESPs and venturi scrubbers plotted as a function of ESP penetration. For this case, no combination of ESP and venturi is less expensive than an ESP or venturi alone. In other cases, not shown here, a combined ESP/venturi system may be the least expensive choice.

A summary of particulate emission control costs for the conditions considered in this case study is presented in Figure 5. The range of costs for fabric filters represents a bag-life range of between 0.5 and 4 years. A cold-side ESP and a fabric filter are cost competitive for low-resistivity ash, while a fabric filter is clearly the most economical choice for ashes with higher resistivity.

IMPACT OF THE REVISED NSPS FOR SO_2

The revised New Source Performance Standard (NSPS) for SO_2 promulgated by EPA in May 1979 requires 70 percent SO_2 removal for low-sulfur coals containing less than about 430 ng/J sulfur (1 lb/10^{6}Btu). Teknekron Research, Inc., has shown that the use of a spray dryer (dry scrubbing) for SO_2 control is less costly than the use of wet FGD systems for these low-sulfur coals.[9] This fact has a number of implications for the choice of a particulate control strategy:

- Particulate control is downstream instead of upstream of the FGD system
- Gas temperature is lower (65-80°C) and closer to the dew point
- Cold-side ash resistivity is lower for most ashes
- Gas flow rate is lower
- ESPs are cost competitive with fabric filters

These implications clearly illustrate the need to evaluate particulate control and SO_2 control as an integrated system in order to select the most reliable and cost-effective control technologies for a given application.

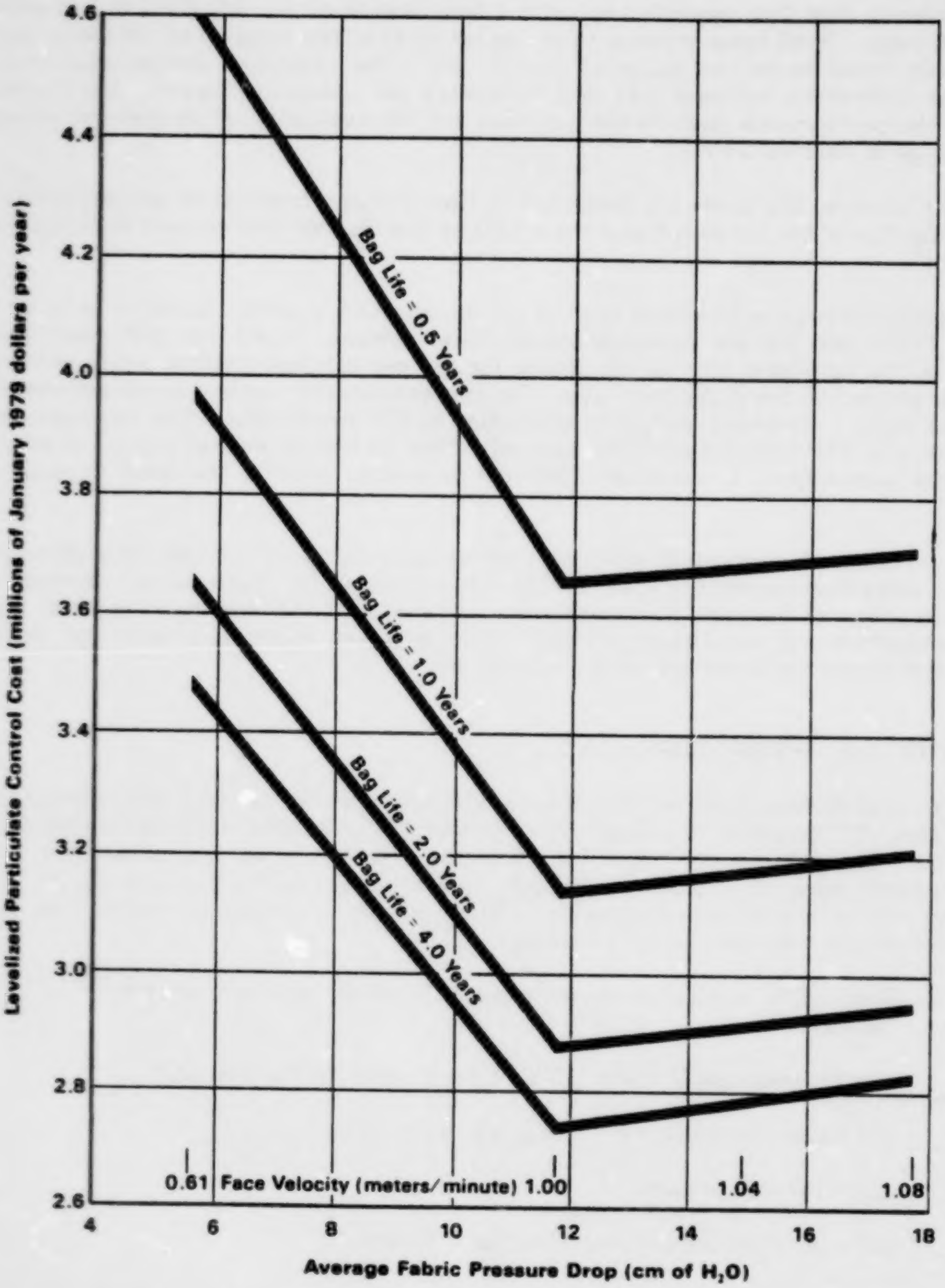

Figure 2. Cost to achieve 99.65 percent particulate removal for fabric filters of various designs for a 500-MW boiler.

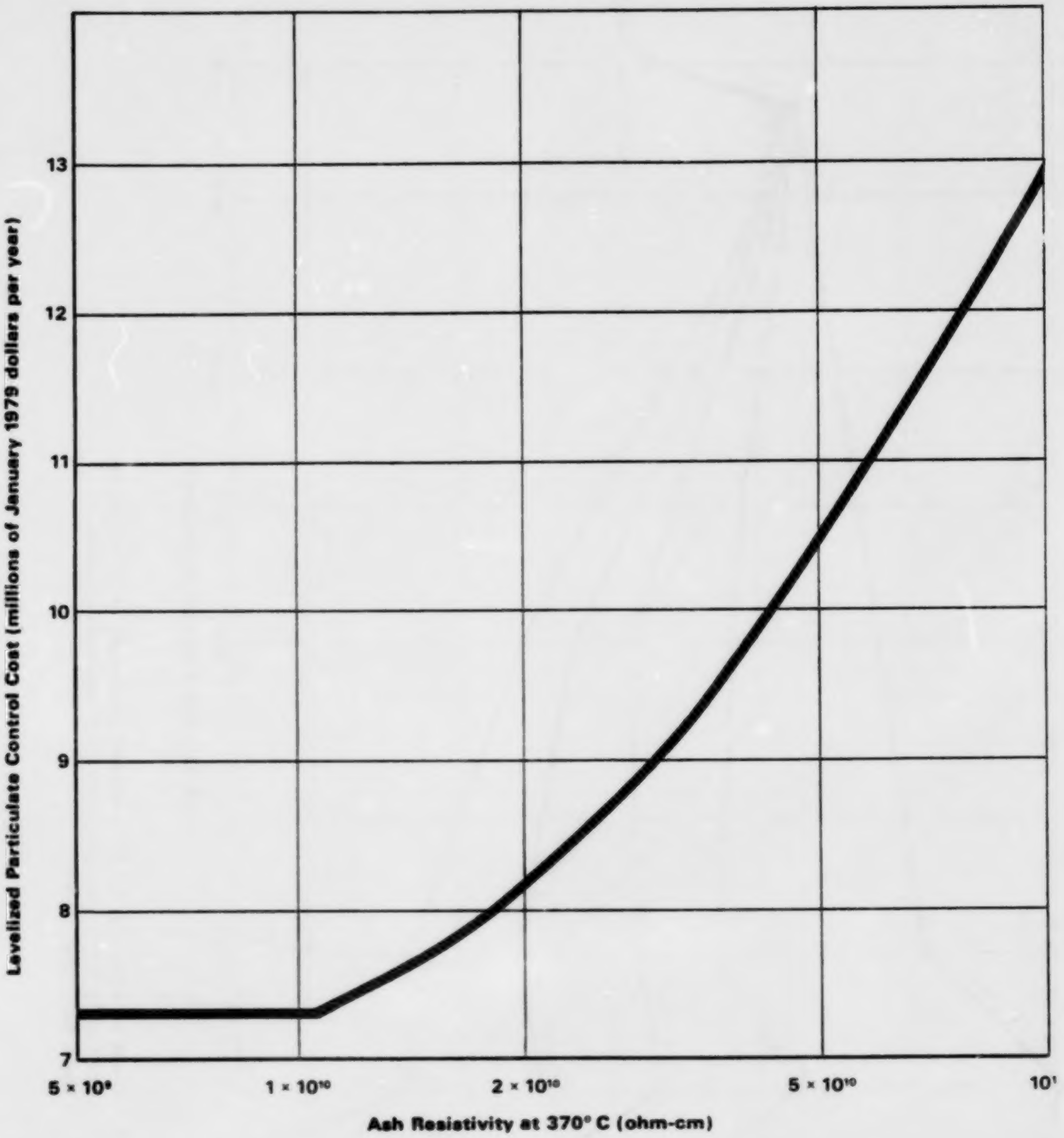

Figure 3. Cost to achieve 99.65 percent particulate removal with a hot-side ESP as a function of ash resistivity for a 500-MW boiler.

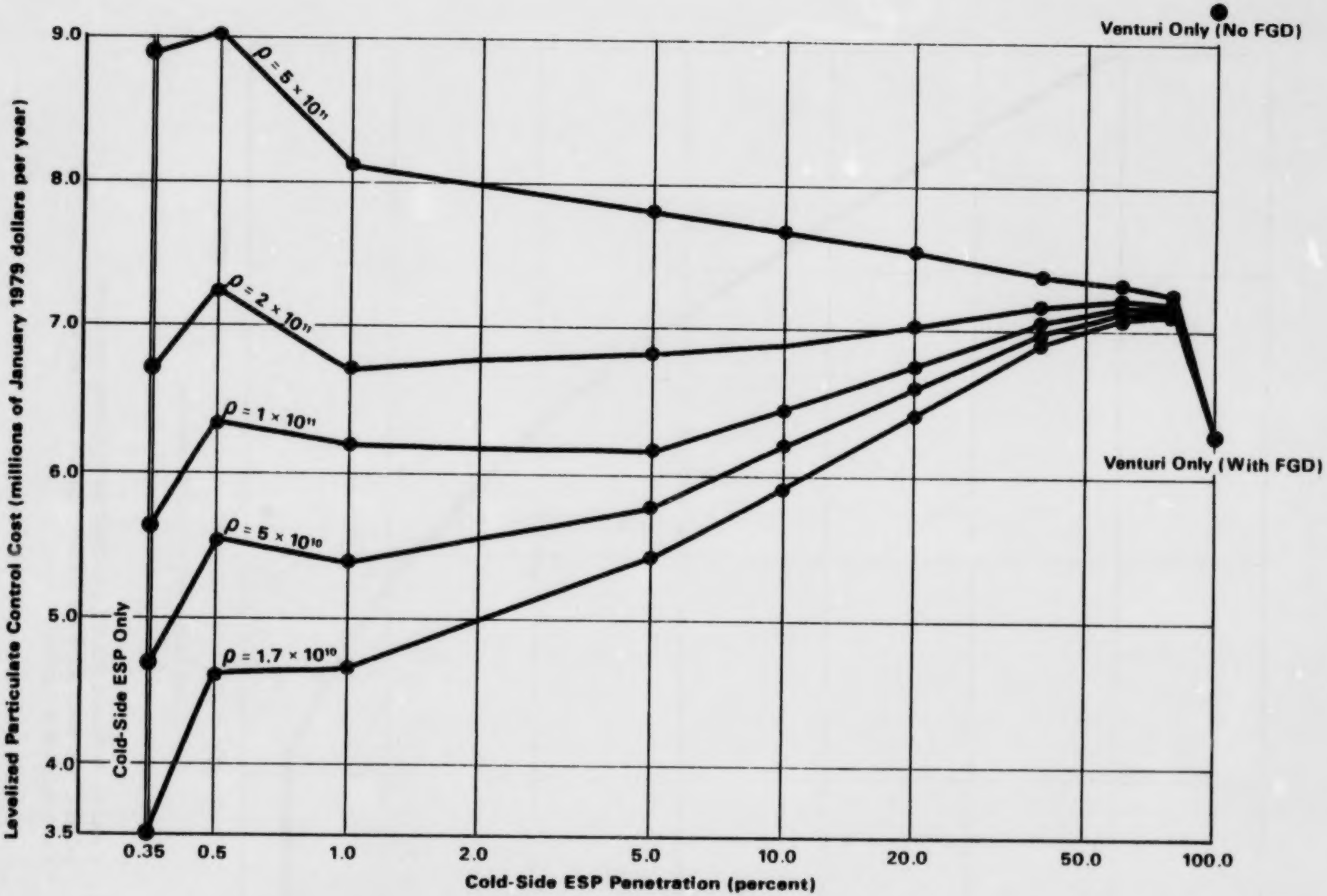

Figure 4. Cost to achieve 99.65 percent particulate removal for cold-side ESP, venturi, and ESP/venturi systems for a 500-MW boiler.

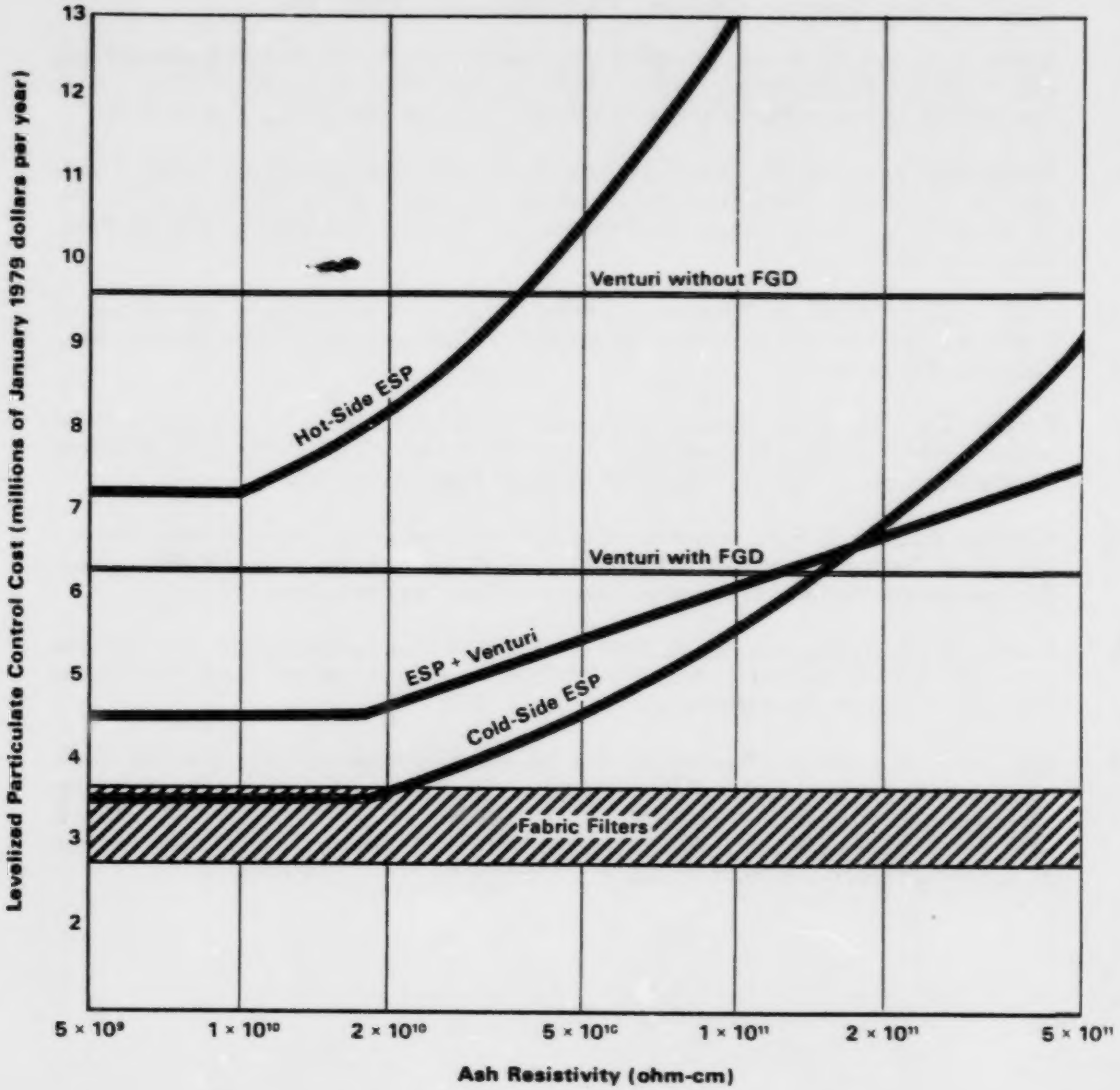

Figure 5. Cost to achieve 99.65 percent particulate removal for various control technologies as a function of ash resistivity for a 500-MW boiler.

REFERENCES

1. Dennis, R., and H.A. Klemm. Fabric Filter Model Format Change; Volume I. Detailed Technical Report. EPA-600/7-79-043a (NTIS No. PB 293551). U.S. Environmental Protection Agency. Research Triangle Park, N.C., February 1979.

2. Stearns-Roger, Incorporated. Economic Evaluation of Fabric Filtration versus Precipitation for Ultrahigh Particulate Collection Efficiency. EPRI FP-775. Electric Power Research Institute. Palo Alto, Calif., June 1978.

3. Sparks, L.E. SR-52 Programmable Calculator Programs for Venturi Scrubbers and Electrostatic Precipitators. EPA-600/7-78-026 (NTIS No. PB 277672). U.S. Environmental Protection Agency. Research Triangle Park, N.C., March 1978.

4. McDonald, J.R. A Mathematical Model of Electrostatic Precipitation (Revision 1): Volume I. Modeling and Programming. EPA-600/7-78-111a (NTIS No. PB 284614). U.S. Environmental Protection Agency. Research Triangle Park, N.C., June 1978.

5. Hall, J.H. Trends in Electrical Energization of Electrostatic Precipitators. Presented at the Electrostatic Precipitator Symposium. Birmingham, Ala., February 23-25, 1971.

6. Ponder, T.C., Jr. et al. Simplified Procedures for Estimating Flue Gas Desulfurization System Costs. EPA-600/2-76-150 (NTIS No. PB 255978). U.S. Environmental Protection Agency. Research Triangle Park, June 1976.

7. Kinkley, M.L., and R.B. Neveril. Capital and Operating Costs of Selected Air Pollution Control Systems. EPA-450/3-76-014 (NTIS No. PB 258484). U.S. Environmental Protection Agency. Research Triangle Park, May 1976.

8. Dennis, R., H.A. Klemm, and W. Battye. Fabric Filter Model Sensitivity Analysis. EPA-600/7-79-043c (NTIS No. PB 297755). U.S. Environmental Protection Agency. Research Triangle Park, N.C., April 1979.

9. Van Horn, A.J. et al. Review of New Source Performance Standards for Coal-Fired Utility Boilers, Phase 3 Final Report: Sensitivity Studies for the Selection of a Revised Standard. Teknekron Research, Inc. Report R-013-EPA-79/R-2. EPA Contract 68-02-3092. Submitted to Office of Research and Development, U.S. Environmental Protection Agency. Washington, D.C., June 1979.

CRITERIA FOR DESIGNING ELECTROSTATIC PRECIPITATORS

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ABSTRACT

The Paper discusses the concepts of effective migration velocity and specific collector area as derived from the Deutsch equation. These two factors are commonly used as a means of specifying a plant size and comparing proposals by different suppliers.

It is demonstrated that effective migration velocity is not a constant dependent only on the fuel, being subject to large variations according to various features of the design of the precipitator. It is also shown that specific collector area cannot be used without at the same time considering the contact time of the gases in the electrostatic field.

The removal of dust by a precipitator is carried out in two stages. The dust is first deposited on the collecting electrode, and a layer of significant thickness must be allowed to form so that when, in the second stage, it is dislodged by rapping, the layer breaks into agglomerated masses sufficiently large to fall into the hoppers below the collecting electrodes before being carried by the moving gas stream into the outlet flue. This requires that the frequency of rapping of each field of the precipitator shall be set at the correct rate according to the concentration of dust entering the field.

Currently much stress is being placed on the intensity of the rapping blow and there is a tendency to specify increasing values of this blow. Due to the necessity to allow a layer of dust to form, no increase in rapping intensity can overcome the effect of highly resistive dust. While the rapping force must be enough to shear the dust layer, any increase above this level is likely to result in the breakdown of agglomerates with an increase in dust emission and may also cause metal fatigue problems.

CRITERIA FOR DESIGNING ELECTROSTATIC PRECIPITATORS

INTRODUCTION

When a specification is drawn up for the design of an electrostatic precipitator for a power station, the information supplied to the designer usually consists of coal and fly ash analyses, dust concentration expected at the inlet of the gas cleaning plant, together with some indications of particle sizing, and the efficiency of gas cleaning required or the guarantee for residual dust concentration in the clean gas.

Recently, in addition to this basic information, it has become the custom to provide additional guides such as the maximum effective migration velocity or alternatively the minimum specific collecting area which will be acceptable, thus avoiding the possibility of grossly under-sized plant being offered. Even more recently there is an increasing tendency to include minimum values of the rapping forces for discharge and collecting electrodes.

It is well known that the fuel and ash composition influence precipitator performance. Equally important, but less well known, is the design of the precipitator which can have a substantial effect on the performance obtained. Incomplete understanding of the basic mechanics of the operation of the precipitator as a dust collecting device can further influence its performance. The object of this paper is to illustrate the effect of the more important factors involved, but due to time, all factors cannot be included, and effort is concentrated, therefore, on the lesser known or more controversial areas.

THEORY OF PRECIPITATION

In Figure 1 is shown the theoretical equation for the calculation of the velocity of a charged particle suspended in a gas in a uniform electric field. This equation gives particle migration velocity, but has no practical application in precipitator design except that it shows that the mobility of the particle will increase with increasing electric field strength. Thus precipitator efficiency could be expected to improve with increasing voltage between the electrodes.

Similarly, particle velocity is opposed by the gas viscosity; this means that particle mobility will decrease as gas viscosity increases, that is with increasing gas temperature. Hence, the probability of the particle being caught would be expected to decrease with increasing gas temperature. This is in line with practice. On the basis of this equation it would also be expected that fine particles would be very difficult to catch effectively in a precipitator. Due to the flow condition of the gas which will be explained later, this is not so, and fine size particles can be readily removed from the gas.

An equation which is commonly used in precipitator design is that derived by Deutsch, also shown in Figure 1. This shows that efficiency will increase with increasing effective migration velocity, and also with increasing value of the ratio of A/V, this ratio being commonly referred to as specific collector area, often used as a means of comparison of different plants.

It must be emphasized that the effective migration velocity (EMV) bears no relationship to the theoretical value from the first equation. EMV is calculated from the size of the precipitator and test efficiencies obtained in operation, and to express the number calculated as migration velocity is misleading.

THE PROPERTIES OF DUST AND GAS

In this section are discussed briefly the properties of dust and gas. These will have similar effects on all types and designs of precipitators. It is often assumed that these properties are the dominant ones in determining the effective migration velocity obtained. As will be seen later, this is not so.

Dust

The effect of particle sizing of the dust is shown in Figure 2, which shows the change in effective migration velocities calculated from the Deutsch equation for different particle sizes for typical highly resistive fly ash. There is some reduction in migration velocity with increasing particle size, with a minimum occurring between 4 and 5 micron. While this change is significant - the ratio being roughly 2 : 1 from the best to the worst condition - it is far less than the pure theory would indicate. The significance of these curves is that as the residual dust requirement becomes lower, or the efficiency of gas cleaning required becomes higher, so the design effective migration velocity must be reduced. Dust in successive fields will become progressively finer. The graph shows that the effect of adding a conditioning agent improves the collection of fine particles selectively probably in part due to improved agglomerate strength.

This graph is for pulverized fuel dust and shows values down to 1 micron. This was the smallest particle size which could be effectively de-agglomerated in pulverized fuel ash. In Figure 3, for interest, is included a similar curve for a wet precipitator working on a metallurgical fuel substantially all below 1 micron in size. This shows that the electrostatic precipitator can collect particles effectively down to the order of 0.01 micron. In this case a minimum migration velocity is shown at 1 micron. The existence of a minimum value for both dry and wet precipitators has been recorded by a number of investigators, although the reason is not fully clear.

Dust Concentration

Dust concentration is important, since apart from the particle sizing effect referred to above, there is evidence that with high dust concentrations, the effective migration velocity is higher, regardless of particle sizing, probably due to the electrostatic field causing some agglomeration of the particles which can fall into the hoppers without actually being deposited on the electrode system. Agglomeration is a very important part of the complete process and will be discussed later.

Figure 4 shows for a sub-bituminous coal the change in migration velocity actually measured on a precipitator with different numbers of fields in operation. It was assumed for the purpose of this exercise that the de-energized fields retained no dust, although this is difficult to prove. On the basis of these measurements, t will be seen that with high dust concentrations of the order of .05 gm/M^3, effective migration velocity was in excess of 8 cms/sec., falling to 4.5 cms/sec. when the dust concentration was less than .05 grams/m^3 which is the concentration for which this plant was designed.

In practice, on this particular plant, the dust emissions measured were in the range .01 gm/M^3 and lower. The effect of this low dust concentration on migration velocity will be referred to under the discussion on the practical features of operation of a precipitator.

If the measured dust emission had been higher, .05 grams/m^3 guaranteed, the curve would have indicated higher migration velocities for the outlet field than the graph indicates, and the slope of the curve would be less steep, due to rapping slip constituting a smaller percentage of the dust.

Dust Resistivity

Much has been written on the subject of dust resistivity. It has been established that at the temperature at the air heater outlet, usually about 121°C, the resistivity of the dust is determined by the surface properties of the dust, and hence the composition of the gas. The occurrence of trace quantities of sulphur trioxide and other conditioning agents can materially affect the efficiency of dust removal.

It has been demonstrated that where these natural conditioning agents are missing, they can be successfully added to the gases to substantially increase the effective migration velocity. The effect of sulphur trioxide and other conditioning agents has been reported by Darby and Whitehead[1] and by other investigators.

Increases in effective migration velocity of more than 2 : 1 have been obtained on a full scale precipitator plant by the addition of as little as 10 p.p.m. of sulphur trioxide. This was first commercially applied on large power plant precipitators by Lodge-Cottrell more than fifteen years ago, and after a period of uncertain popularity, now seems to be becoming an accepted system in the United States.

Other conditioning agents which have been demonstrated with varying degrees of effectiveness include ammonia, triethylamine and water vapor, but sulphur trioxide still appears to be the most cost-effective additive.

Considering the types of coal, in the case of the hard bituminous coals, there is evidence to support the view that the surface resistivity is largely determined by an adsorbed layer of sulphuric acid or a layer of sulphite as in general effective migration velocity increases with increasing combustible sulphur content. There is some scatter of the test points when plotted graphically, but since it is known that other constituents of the ash can also affect the performance, it is not unexpected that the relationship should not be precise.

In the case of the sub-bituminous coals, experience of which has occurred mostly in the American mid West, sulphur content is generally low. In this case, the presence of sodium and potassium compounds in the ash are significant factors.

Figure 5 shows a typical curve for the effect of sodium on effective migration velocity. It is of significance that sodium appears to have a more pronounced effect than potassium, although potassium will also further improve the effective migration velocity.

Conditioning agents, either natural or artificial, have the effect of giving more stable electrical operation of the precipitator at a higher field voltage with the consequent higher efficiency of dust removal. In a paper by Lederman et alia[2], chemical conditioning is also reported to work on a hot side precipitator. In this case, the effect is unlikely to have been to reduce resistivity, since before the air heater, the temperatures are generally in excess of 260 °C, at which temperature all dusts exhibit resistivities well below the accepted critical level.

This paper indicates that the effect of conditioning agents was to increase the breakdown voltage, thus counteracting the effect of the increasing temperature in this respect. For example, breakdown voltage was said to be increased by as much as 50% when using conditioning agents in the form of various salts of sodium and potassium. Apart from the effect on the electric field, in the opinion of the author, a major additional effect was likely to be an increase in agglomerate strength and reduction in re-entrainment.

The comparison of hot and cold side units by Darby and Whitehead[3] shows that despite the reduction of resistivity, the effective migration velocity at the high temperature was not always higher than on the cold side. Due to this and the effect of increased volume due to higher temperature, the hot side plant could in many cases be larger than for the cold side. It now seems proven that the hot side approach has limited application and is not the panacea which would enable variations in fuel and ash properties to be ignored. The consideration of the use of conditioning agents on hot side units is confirmation that this is so.

The Properties of the Gases

On the standard cold side approach to the application of precipitators, it is difficult to separate the effect of gas composition completely from that of the dust. For example, in the case of sulphur conditioning, the effect is probably due to an adsorbed layer of acid vapor. Reduction of the resistivity of the deposited layer of dust has the effect of increasing stability of operation and reducing reverse ionization effects. It is also known that increasing the sulphur dioxide content of the gas also increases the breakdown voltage, thus giving additional benefit, so that for example an increase in combustible sulphur in the coal has a double effect.

In addition to the resistivity effect on the dust, more stable operation and higher voltages often result as an additional effect from the presence of significant quantities of conditioning agents, in particular water vapor.

Brown coal with very high water content, over 60% by weight but containing no other recognized conditioning agent, has given test values of effective migration velocity well in excess of 10 cms/sec.

EFFECTS OF PRECIPITATOR DESIGN

The Mechanism of Collection of Dust by Precipitator

The single stage plate precipitator, the type universally used in power plants, consists of a horizontal flow gas chamber containing varying numbers of electric fields in series. (See Figure 6.) The gas enters at a velocity (V) in the range of 9 - 21 m/sec. and is reduced by gas distribution devices so that the velocity over the whole cross section of the field is uniformly of value (v) usually in the range of about .9 - 1.8 m/sec.

Consider first the effect of the electric field. In the single stage precipitator with a non-uniform electric field, flow conditions are in the turbulent range and increased turbulence is created by the effect of the electric wind resulting from the corona discharge. The net effect is that the turbulent velocity of the gas is high compared with that of the velocity of the particles through the gas under the influence of the electric field. The consequence of this turbulence is that dust particles are brought into close proximity to the collection electrodes, and the probability of being caught is determined by this proximity, which has the effect of largely cancelling out the reduction in efficiency of collection of small particles suggested by the fundamental equation. Dust is, therefore, deposited for a wide variety of particle sizing in each successive field with only comparatively small reduction in the mean particle sizes in the successive fields.

After the particles have been deposited on the electrode system or in a small percentage of cases on the discharge system, they cannot at this stage be regarded as effectively removed from the gas stream.

The next stage in the precipitation process is to remove the dust so deposited either by vibrating or rapping mechanically to dislodge the layer of dust so that it falls into the hopper below the precipitator. Only then can the dust be regarded as 'caught'.

Figure 7 shows free falling velocity of different particle sizings, from which it will be clear that individual particles of fly ash dislodged from the collecting electrode would only fall at a very low velocity of less than .03 m/sec. towards the hopper. At the same time they are carried forward through the chamber at the gas velocity (v), so that very few would reach the hoppers.

Further considerations of the mechanism of collection shows that the precipitator can only effectively collect dust when the deposited layer, on being sheared from the electrodes, stays in the form of agglomerated masses sufficiently large to give a high velocity sufficient to reach the hoppers before the gases accelerate again into the outlet flue, at which point the dust can be regarded as effectively not caught.

Consideration of the graph shows that the mean size of the aggomerates needs to be in excess of 1 mm (1000 micron) in order to have free falling velocities in excess of 3 m/sec. It is in fact a vital part of the precipitation process that a layer of significant thickness is allowed to build up in order to permit the formation of the necessary size of agglomerate. In practice, the size of the agglomerates is related to the molecular forces between the particles and in particular the natural adhesiveness which often is a contributory effect of a conditioning agent.

When any form of rapping takes place to dislodge the dust, the layer breaks down into masses of varying sizes. One of the most important features of the rapping mechanism is that it must be designed so that the frequency of rapping permits the necessary layer to accumulate, and the intensity is sufficient to dislodge the layer with the minimum breakdown of the agglomerates.

The rate of dust collection in the successive stages as predicted by the Deutsch equation shows an exponential relationship. For example, in a three field precipitator in series designed for 99.9% efficiency, the first field would retain approximately 90%, the second 9% and the third field 0.9% of the dust in the gases.

This is in practice a rough approximation as the effect of particle size, dust concentration, etc., is ignored, but from this it will be seen that the rapping frequency in order to permit the same thickness of layer to build up must be very much lower on the outlet field, approximately 1/100 of the frequency of the inlet field. The rapping of the outlet field is most critical as there is no further chance to catch re-entrained dust.

Figure 8 shows the variation of effective migration velocity for a single field with intervals between the rapping blows. A high rate of rapping, i.e. every 15 seconds, gives an effective migration velocity of 6.3 cms/sec. compared with 10 cms/sec. when the frequency is reduced to once in 1,000 seconds. These data were obtained on an inlet bank with a dust concentration of the order of 23 grams/m^3. At a frequency of 10 rapping blows/hour, the higher migration velocity was maintained; at longer intervals, a gradual fall-off over several days was observed. This frequency was adopted as a general standard for this dust concentration, and has proved satisfactory for most conditions. For successive banks, the optimum frequency was found to be correspondingly less. Outlet fields may only need rapping at intervals of several hours, long enough to permit a layer of significant thickness to build up so that when dislodged by rapping, the agglomerates reach the hopper quickly. Consideration of Figure 8 shows that the frequency is not highly critical, so the same frequency can be used for a range of different coals without serious effects on performance.

The other variable in rapping is the intensity. Currently, high intensity rapping is being put forward as a cure for many of the problems resulting from highly resistive dust. Considered in light of the fact that it is the presence of a deposited layer which creates problems, it would appear logical to increase rapping intensity. On the other hand, in view of the need to accumulate a layer of dust which is the essential to the formation of agglomerates heavy enough to fall to the hopper, it is obvious that achieving the objective of minimizing the dust layer on the collector to a degree where high resistivity is no problem will result in a considerable increase in re-entrainment of dust due to the smaller agglomerate size which will result. This will more than negate the effect of the advantage obtained in electrical operation. The layer of highly resistive dust which can be tolerated without affecting the electric field is reported as less than 1 mm. This, taken together with Figure 6, illustrates the limitation on improvement in efficiency which changes in rapping frequency and intensity can be expected to achieve.

In the experience of the author, there is no evidence that high intensity rapping has contributed any significant improvement to efficiency under highly resistive dust conditions. In a recent paper by Juricic and Herrmann[4], Juricic carried out interesting laboratory experiments on the dislodgment of dust, and a very interesting film, using high speed photography, showed how the dislodged layer was broken into agglomerated masses which fell to the hopper. Furthermore, increasing displacement of the collector due to higher intensities resulted in disintegration of some of these agglomerates.

Their paper was the result of a limited research programme which might add much to the knowledge of the precipitation process if continued. In contrast to what might be expected, high intensity rapping can be disadvantageous for many types of dust where the agglomerate strength is not high. Surprisingly, the benefit is more likely to result with highly conditioned dust resulting from, for example, high sulphur fuels, where with normal intensity rapping there can be a progressive build up of significant thickness, i.e. in excess of one inch, which can influence the operation of the plant by reducing clearances and modifying the corona discharge.

Dalmon[5] in an unpublished report stated "accelerations of the order or 10g removed most of the dust, but left the surface coated with a layer of dust so tenacious that they are not dislodged by forces an order higher (100g)".

In a paper presented at a recent Conference, he further concluded that for U.K. coals, 60g was the rapping force most likely to produce the required effect on collecting electrodes. This would not necessarily be true for all types of coal. In practice, the forces used should be verified for different fuel compositions. Excessive forces can result in breakdown of agglomerates and also increase the risk of failure from metal fatigue problems.

In current specifications, the value of rapping force is tending to increase and minimum requirements of over 100g are sometimes specified. There is a danger that unless the problem is fully appreciated, these high values could be expected to increase mechanical problems.

Aspect Ratio

Aspect ratio is a term which has been used in the last few years as a means of regulating the ratio of field length to field height, and is in fact a ratio of these two quantities. In Figure 6 this would be represented by (3*1)/H. The object of specifying a value of Aspect Ratio, although often not appreciated, is to ensure the maximum possibility of agglomerates having time to reach the hopper, i.e., if taller collecting electrodes are used then the field length must correspondingly increase to give comparable conditions to shorter collectors. Using this concept. aspect ratio should also increase as the efficiency of dust removal required increases and the residual dust decreases - it is not a constant for all conditions.

Examination of Figure 6 will show that the significant factors determining whether dust reaches the hopper should include the time that the gas remains in the chamber. Wherever the agglomerate is released from any point on any collecting electrode, it will only be retained effectively by the precipitator when the time interval which elapses from when it is released to when it leaves the chamber is equal to or greater than that needed to fall to the quiescent hopper zone below the collecting electrodes. This time will obviously vary according to the position in the field, but the maximum time available is given by the ratio of L/v where L includes the inter-bank spaces in addition to the actual length of the electrostatic field. This is permissible since in this space the dust is also still falling towards the hopper.

Dust will be retained effectively by the precipitator only if the dust reaches the hopper, and this in turn means that the outlet bank is particularly critical so far as rapping and size of dislodged agglomerate is concerned. Dust leaving the outlet upper end of the collector, B in the diagram, will mostly fall on the outlet slope of the flare, but some will be carried into the outlet flue and become part of the dust emitted from the precipitator.

The object of Figure 6 is to illustrate that gas velocity must be included in the consideration of the problem. In place of the present concept of aspect ratio, it is suggested that from the point of view of dust collection, the geometry of the gas chamber is better expressed when comparing different designs as the ratio t/H where t is the time the gas is in the precipitation chamber and H is the collecting electrode height. This ratio shows that increasing the height of collector is permissible only if contact time of the gases within the precipitation chamber also increases. The height of the precipitator collector in practice is essentially a compromise, designed to give the lowest re-entrainment slip, together with the most economic construction.

Due consideration of the mechanics of dust collection, re-entrainment etc., make possible the design of precipitators giving residual dust emissions well below .02 grams/m^3. While the correct rapping is important on all fields, the minimizing of rapping slip on the outlet bank is most critical as this has least chance of being re-deposited.

Generally, single blows with an impulse hammer give the least re-entrainment slip. Any form of vibrator, since the time of operation is longer than a single hammer blow, will cause a greater re-entrainment slip. Similarly, if in order to maintain a high average rapping force "g" over the whole collector, a number of hammers are used at different points, this has the effect, so far as rapping re-entrainment slip is concerned, of increasing the frequency of rapping, since it is not possible to precisely synchronise the blows. In such a case, while in some areas the rapping intensity may be below the level needed to shear the dust layer, re-entrainment of the newly deposited dust on the surface will still take place.

Gas Distribution

From Figure 6 and from examination of the Deutsch equation, it is apparent that the best efficiency, assuming all other factors are optimized, is obtained when:

1. The gas distribution is absolutely uniform over the whole cross section of the field.

2. No gas by-passes the electrostatic field either in the roof or hopper regions.

It is not practical to carry out gas flow correction work in the field on the full scale unit, and the custom is, therefore, to use standard wind tunnel techniques with large scale models. These models should preferably be as large as possible. Lodge-Cottrell custom is to construct no smaller than one-eight of the full size, as it is believed that the scale factor for small models introduces significant errors into the final distribution pattern.

Figure 9 shows the effect on precipitator efficiency of varying degrees of gas distribution correction expressed in terms of percentage deviation from ideal. Under ideal conditions the precipitator would give 99% efficiency. Standards laid down by the I.G.C.I. would give roughly 98.8% efficiency while poor distribution can give efficiencies well below 97%. Since this is due to poor distribution, the efficiency could be brought back to the desired level by increasing the plate area and the size of the plant. The plant would give on test a lower effective migration velocity.

In practice, a perfectly uniform distribution over the whole field is not possible, particularly at the upper and lower extremities. It is very important that the full height should be utilized and at the same time gas should not by-pass the electrostatic field. Figure 10 shows, for varying precipitator efficiencies, the effect on the calculated effective migration velocity of a 0.1%, 0.5% and 1% by volume by-pass.

As would be expected, the effect is small in all cases when the design efficiency of the precipitator is only 80%, but when efficiencies of 99.9% for example are required, even the 0.1% condition, with perfect collection of the dust passing through the field, can only just reach the desired efficiency. In present day plants, therefore, where high efficiencies are guaranteed, the permissible by-pass effectively must be considerably less than 0.1%. This is achieved by baffling, which prevents the gas completely by-passing the field for the complete length of casing. For example, 0.1% of the gas having partial treatment by looping in and out of successive banks (See Figure 6 - upper and lower ends of plate) can be reduced in significance to an acceptable level. In practice, measured efficiency on dry plant in excess of 99.99% have been obtained, thus verifying that with the correct approach to this problem, the effect of by-pass can be made insignificant.

Electrical Conditions

The electrical conditions, i.e., the D.C. voltage and corona current applied to the electrode system, are determined by the geometry of the precipitator. It can be shown that for any plant design, the highest mean voltage which can be applied to the electrode system will result in the highest efficiency of dust removal.

Thus if the design in any way limits this voltage, measured effective migration velocity will also be reduced. The ultimate aim of all precipitator automatic control system, whether they operate by measuring electrode voltage or by spark counting, is to apply at all times the highest possible voltage to the electrode system.

Figure 11 shows the variation of effective migration velocity with increasing total current applied to the electrode system. Total current is the term used, since while the current is almost entirely corona discharged at the lower voltages, ultimately most of the power is absorbed in power arcs which contributes nothing to the precipitator efficiency if the applied voltage is too high.

The graph shown was derived by the Central Electricity Generating Board to test the theory of the control system which in this case operates on high tension voltage. It will be seen that there is a large variation in effective migration velocity between either under-running or over-running the rectifier compared with the optimum setting. This can be a most significant factor when a plant efficiency is measured by sampling; it is very important that the rectifier control system is correctly designed and is also functioning correctly.

The conditions inside the gas chamber which determine voltage and current which can be carried safely vary with dust and gas loading, and the nature of the coal, so that the control system cannot operate at a pre-set voltage or current input.

A second factor which has long been recognized in the precipitation industry, but for which no theoretical explanation exists, is the effect of the bus section size energized by one rectifier set. Figure 12 shows the change in effective migration velocity with increasing bus section size, shown as the size of collector electrode plate connected to a single rectifier. The effective migration velocity varies from over 10 cms to approximately 6.5 cms for plate areas ranging from 450 m^2 to 7500 m^2. This effect was also reported by Ramsdell[6].

The choice of plate area and the number of bus sections is determined by the most economic combination, striking a balance between the cost of the rectifiers and the cost of the precipitator and internals. An important point to remember is that rectifier costs do not decrease proportionately with decreasing current output rating. Also additional bus sections require additional rapping and lead-through insulators which add to the cost.

Plate Spacing

Plate spacing is probably one of the most controversial factors in precipitation. Examination of the Deutsch equation would give the impression that A/V, the specific collector area is, apart from effective migration velocity, the most significant factor, being directly related to precipitator efficiency.

Taken to its logical conclusion, the implication of this formula is that for a particular precipitator casing size and contact time, the closer the plates can be spaced, the more efficient the precipitator will be.

There are obvious practical limitations to this argument because of the difficulty in manufacturing large collecting plates (up to 15.2 m x 4.6 m) to the necessary degree of flatness, and hence extremely low spacings are automatically eliminated.

Similarly with the discharge electrodes, the same limitations are imposed although these are less in the case of weighted wire than in the rigid electrode constructions. Plate spacings on commercial plant currently in use range from 203 mm (8") to 610 mm (24") and even higher, but most commonly are in the range of 203 mm to 305 mm.

Figure 13 shows the results of tests carried out on a full-scale boiler plant with the plates spaced at 305 mm and 610 mm. Due to the fact that the precipitator casing was designed for 305 mm spacing, the electrical conditions for the 610 mm space were artificially limited.

The tests were taken with a wide variety of fuels which explains the scatter of the test points. Even so, there is seen to be an increase in average migration velocity of from 12 to 18 cms when the plate spacing is increased from 305 mm to 610 mm.

The tests were carried out on a C.E.G.B. power station a few years ago, and patent applications were made to cover this wide spacing approach. A number of plants have been installed with more than 508 mm spacing for applications where expensive materials of construction were needed, and this effect was particularly favorable on cost. In the case of power stations, since with increasing plate spacing, the casing must also increase in size, a review of economics indicated that spacings of the order of 305 mm were an acceptable compromise.

It is interesting to note that apart from the work by Lodge-Cottrell, the effect has also been recorded in papers by Misaka et alia[7] and Aureille and Blanchot[8]. Both these papers showed a greater increase in effective migration velocity with spacing than the Lodge-Cottrell tests. Currently spacings in excess of .6 m have been mentioned as a standard approach of Nippon Steel in their publications, and similar spacings are being used by yet another Japanese manufacturer.

Considering the implications of this effect, together with the tendency to quote plant size in terms of specific collector area, which assumes that migration velocity is constant regardless of plate spacing, then it would seem that the present methods using either effective migration velocity or specific collector area do not give a correct comparison of plants of different designs where the spacing of the plates vary.

The effective migration velocities measured in all cases quoted were for the same contact time, the same gas velocity in the field and the same inlet dust conditions. Thus there is little doubt that the wider spacing resulted in an increase in effective migration velocity. In practice, use of wider spacing with the same collector area must also at the same time give an equally proportionate increase in contact time. In view of the importance of time in the field in collecting agglomerates after they are removed from the collectors, the wider spacing plant at the same plate area has the double potential advantage of a higher effective migration velocity and a longer 'contact' time in the precipitator casing than a smaller spaced plant for similar fuel and gas conditions.

CONCLUSION

The Deutsch equation is commonly used for electrostatic precipitator size calculations. It contains two terms, effective migration velocity and specific collector area. The first of these is often considered to be determined only by the properties of the coal and ash. In practice, since effective migration velocity is calculated from the size of the precipitator and measured dust removal efficiency, it is also strongly influenced by a number of design features of the precipitator plant. These include gas distribution, rapping frequency and intensity, electrical operation, dust concentration and dust sizing distribution.

Comparing plant size in terms of specific collector area assumes that effective migration velocity is constant regardless of spacing. There is strong evidence to support the view that effective migration velocity does in fact increase with plate spacing. Furthermore, the mechanism of the dust collection process, which has been shown to depend on agglomerate formation sufficiently heavy to fall to the hoppers, supports the argument that the time that the gases are exposed to the electrostatic field must also be taken into account. This increases with plate spacing for the same collector area so that when comparing plant of different design, not only must correction be made for effective migration velocity for the different plate spacing, but also with the wider plate spacing there is the added advantage of increased time in the field which can only result in a further increase in precipitator efficiency for which additional credit must be given.

The whole mechanism of the removal of the dust from the collector plate and the manner in which it is transferred to the hoppers is a subject which requires a considerable amount of additional study. While the forces needed to dislodge the dust layer must be sufficiently large to keep the plant reasonably free of dust, this should not be so great that the motion induced in the collector is sufficient to start break-up and reduction in the size of the agglomerates, and hence increase the re-entrainment slip. For this reason, the present trend towards specifying progressively higher acceleration forces for rapping must be treated with caution.

REFERENCES

1. Busby, H. G. T. and Darby, K. Efficiency of Electrostatic Precipitators as Affected by the Properties and Combustion of Coal. Institute of Fuel, May 1963.

2. Lederman, P. B. and Bush, J. Chemical Conditioning of Fly Ash for Hot Side Precipitators. CSIRO Conference on Electrostatic Precipitators. Australia 1978.

3. Darby, K. and Whitehead, C. The Use of Electrostatic Precipitators in Current Power Station Practice. Institute of Fuel Symposium on Changing Technology of Electrostatic Precipitation, Adelaide, Australia 1974.

4. Juricic, D. and Herrmann, G. Modeling and Simulation of Dust Dislodgment on Collecting Plates in Electrostatic Precipitators. EPRI Sponsored Project Research Contract RP533-1.

5. Dalmon, J. Investigation into Forces Required to Dislodge Precipitated Dust from an Electrode. Unpublished CEGB Report.

6. Ramsdell, R. G. Design Criteria for Precipitators for Modern Central Station Power Plant. American Power Conference, 1968.

7. Misaka, T., Sugitomo, K. and Yamada, H. Electric Field Strength and Collection Efficiency of Electrostatic Precipitator having Wide Collecting Plate Pitches. CSIRO Conference on Electrostatic Precipitators, Australia, August 1978.

8. Aureille, R. and Blanchot, P. - Electricite de France. Experiments to Test the Influence of Different Parameters on Electrofilter Efficiency. Staub 31, 1971.

FIGURE 1

ELECTROSTATIC PRECIPITATOR

THEORETICAL MIGRATION VELOCITY

MOTION OF CHARGED PARTICLE IN ELECTRIC FIELD

$$w = \frac{p E^2 a}{6 \pi \mu}$$

p VARIES WITH PROPERTIES OF MATERIAL 1·5-3 FOR AVERAGE INSULATING MATERIALS
E ELECTRIC FIELD STRENGTH
a PARTICLE RADIUS
w PARTICLE MIGRATION VELOCITY
μ GAS VISCOSITY

DEUTSCH EQUATION

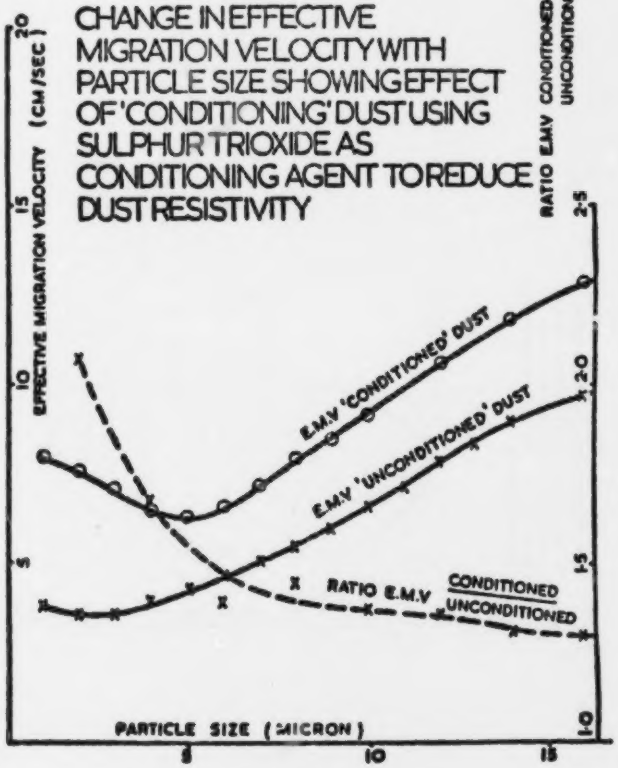
EFFICIENCY $= 1 - e^{\frac{sl}{dv}}$

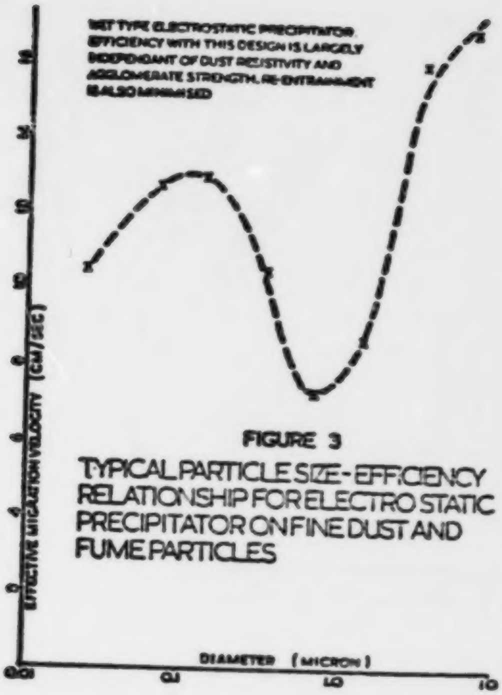
$= 1 - e^{s\frac{A}{V}}$

SPECIFIC COLLECTOR AREA $= \frac{A}{V}$

s - EFFECTIVE MIGRATION VELOCITY
l - FIELD LENGTH
v - GAS VELOCITY
d - ELECTRODE SPACING
A - TOTAL PLATE AREA
V - GAS VOLUME THROUGH PRECIPITATOR

FIGURE 2


CHANGE IN EFFECTIVE MIGRATION VELOCITY WITH PARTICLE SIZE SHOWING EFFECT OF 'CONDITIONING' DUST USING SULPHUR TRIOXIDE AS CONDITIONING AGENT TO REDUCE DUST RESISTIVITY



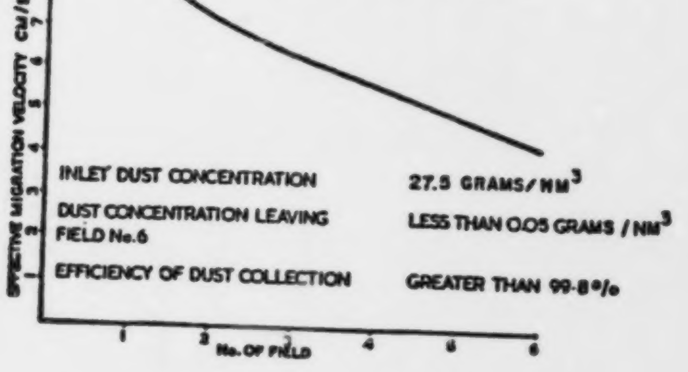
WET TYPE ELECTROSTATIC PRECIPITATOR. EFFICIENCY WITH THIS DESIGN IS LARGELY INDEPENDANT OF DUST RESISTIVITY AND AGGLOMERATE STRENGTH. RE-ENTRAINMENT IS ALSO MINIMISED

FIGURE 3

TYPICAL PARTICLE SIZE - EFFICIENCY RELATIONSHIP FOR ELECTRO STATIC PRECIPITATOR ON FINE DUST AND FUME PARTICLES

FIGURE 4

CHANGE IN EFFECTIVE MIGRATION VELOCITY IN SUCCESSIVE FIELDS OF PRECIPITATOR DUE TO REDUCING DUST CONCENTRATION AND INCREASING FINENESS OF RESIDUAL DUST



INLET DUST CONCENTRATION	27.5 GRAMS/NM^3
DUST CONCENTRATION LEAVING FIELD No.6	LESS THAN 0.05 GRAMS / NM^3
EFFICIENCY OF DUST COLLECTION	GREATER THAN 99·8 %

FIGURE 5
SUB-BITUMINOUS COALS AND LIGNITES
VARIATION IN PRECIPITATOR SIZE WITH VARIATION
IN THE SODIUM OXIDE CONTENT OF THE COAL ASH

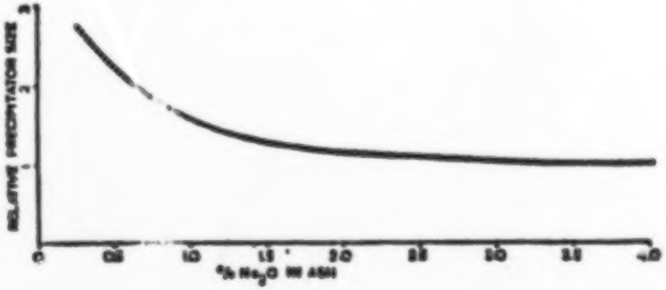
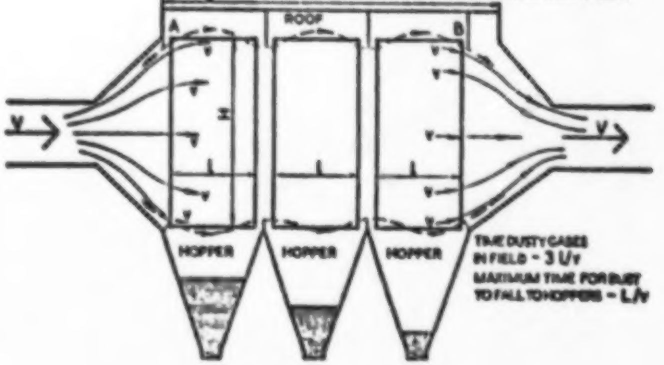


FIGURE 6
IDEAL CONDITION – UNIFORM VELOCITY v OVER FULL HEIGHT AND WIDTH OF RECEIVING ELECTRODES
– NO MOTION IN ROOF OR HOPPER



L
ROOF
A
B
H
v
HOPPER
HOPPER
HOPPER
TIME DUSTY GASES IN FIELD – 3 L/v
MAXIMUM TIME FOR DUST TO FALL TO HOPPERS – L/v

FIGURE 7

FREE FALLING VELOCITY OF SPHERICAL PARTICLES SPG 2 IN AIR AT 20°C AND 760mm HG PRESSURE

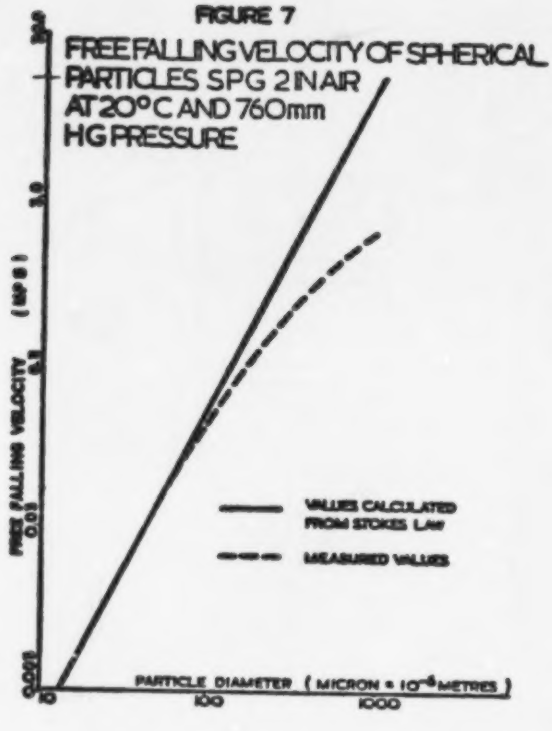


FIGURE 8

EFFECT OF RECEIVING ELECTRODE RAPPING FREQUENCY ON EFFECTIVE MIGRATION VELOCITY (INTENSITY CONSTANT)

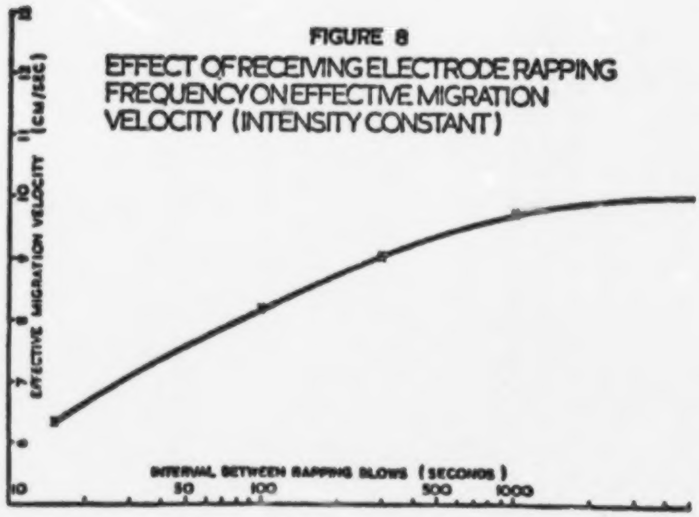


FIGURE 9
VARIATIONS OF EFFICIENCY AGAINST GAS DISTRIBUTION
ASSUMING 99% EFFICIENCY UNDER IDEAL CONDITIONS

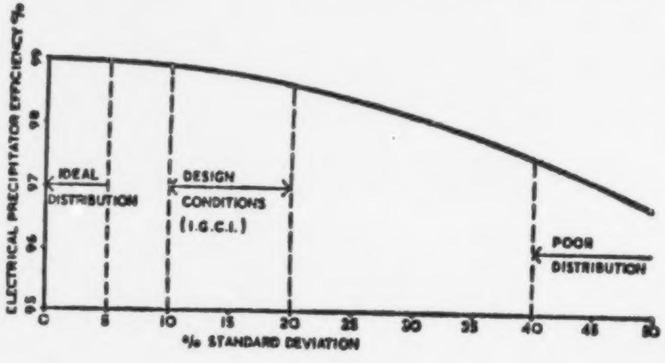


FIGURE 10
EFFECTIVE MIGRATION VELOCITY AND PRECIPITATOR EFICIENCY FOR VARYING PERCENTAGES OF GAS BY-PASSING ELECTRODES SYSTEM

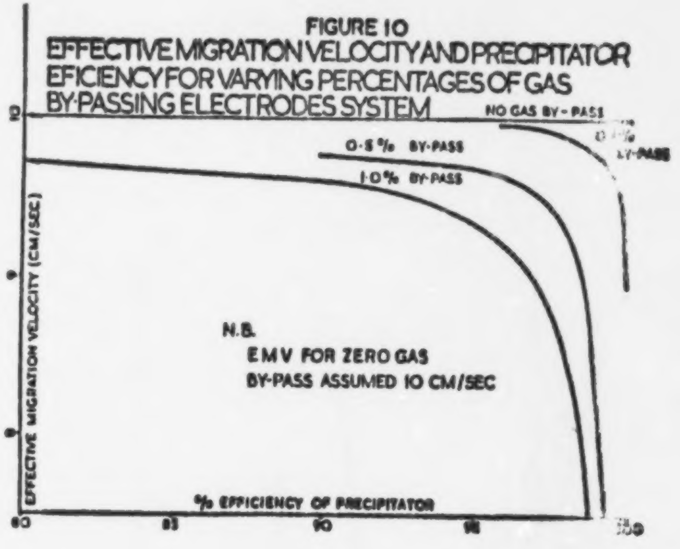
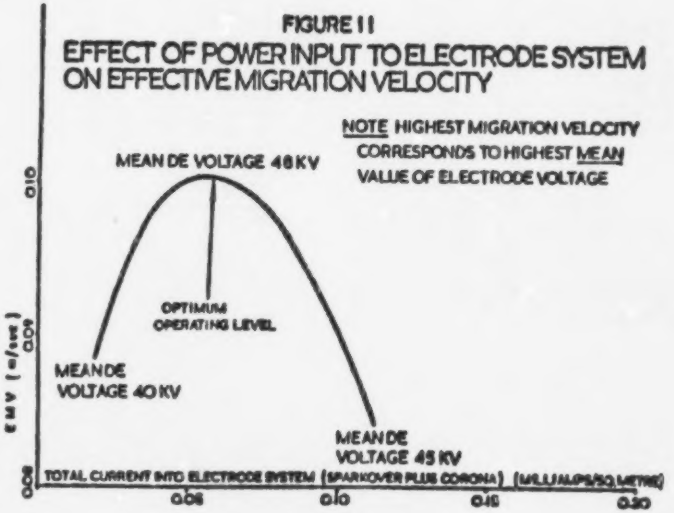


FIGURE 11
EFFECT OF POWER INPUT TO ELECTRODE SYSTEM ON EFFECTIVE MIGRATION VELOCITY



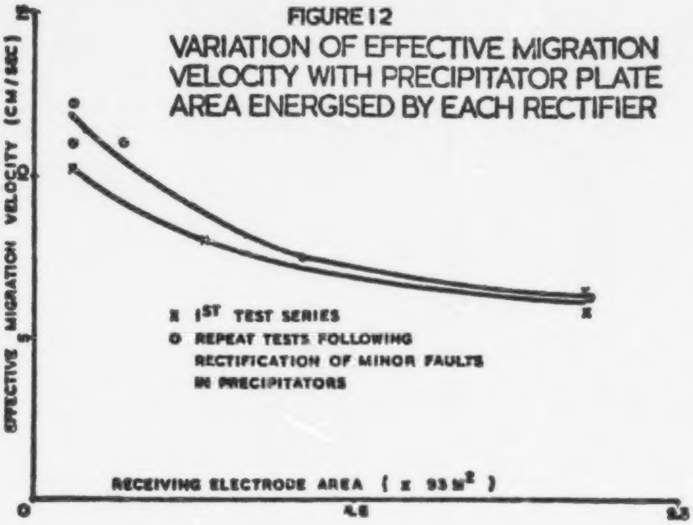


FIGURE 12

VARIATION OF EFFECTIVE MIGRATION VELOCITY WITH PRECIPITATOR PLATE AREA ENERGISED BY EACH RECTIFIER

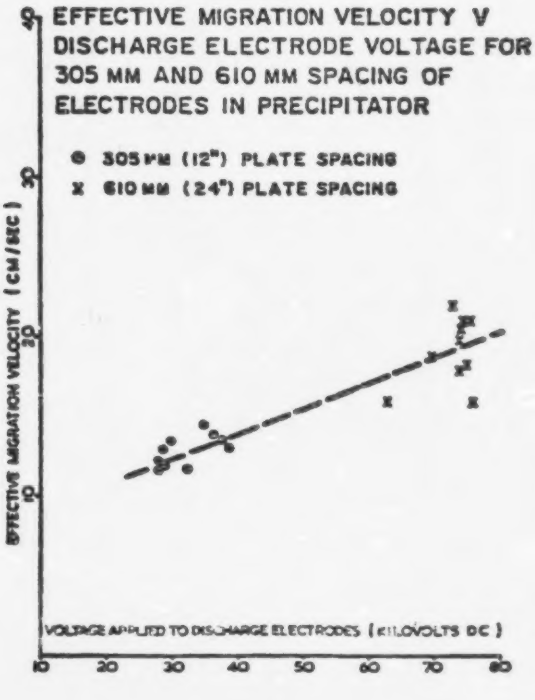


FIGURE 13

EFFECTIVE MIGRATION VELOCITY V DISCHARGE ELECTRODE VOLTAGE FOR 305 MM AND 610 MM SPACING OF ELECTRODES IN PRECIPITATOR

EVALUATION OF THE GEORGE NEAL ELECTROSTATIC PRECIPITATOR

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ABSTRACT

The Electric Power Research Institute (EPRI) is currently supporting a major research program characterizing the performance of high efficiency electrostatic precipitators (ESP). One such effort evaluating the George Neal ESP of Iowa Public Service Company is described in this paper.

Results show that under well tuned conditions the ESP overall collection efficiency was 99.7 percent at a specific collecting area of 745 ft^2/kacfm (520 MW) with associated mass concentrations of 0.025 lb/10^6 btu and stack opacity of 4.6 percent. The boiler outlet size distribution was found to be bimodal with submicron and large particle peaks at 0.2 and 5 microns diameter, respectively. Consequently, an apparent bimodal fractional efficiency curve results with efficiencies of 99.6, 98 and 90 percent measured for 20, 2 and 0.2 micron diameter particles, respectively. Rapping reentrainment losses were found to be insignificant except during episodes of high ash hopper levels resulting from a malfunctioning ash removal system, when large rapping puffs were observed. In addition, outlet emissions increased dramatically to 0.08 lb/10^6 btu during these periods, suggesting that an emission level more representative of daily operation lies somewhere between 0.025-0.08 lb/10^6 btu.

INTRODUCTION

It has become apparent that regulatory agencies are intent on reducing permissible particulate emissions from pulverized-coal fired utility boilers. The most recent example is the 0.03 $^{lb}/10^6$ btu revised New Source Performance Standard promulgated by EPA. An even more striking example is evident in California, where the State Air Resources Board has defined Best Available Control Technology as 0.005 lb/10^6 btu, or equivalent to 99.9+% control for new coal-fired boilers. In addition, increasing attention is being directed to control of fine particulates (less than 2 micron particle diameter), trace element emissions and plume opacity.

In response to these regulatory constraints the utility industry, through the Electric Power Research Institute (EPRI), is conducting a major research program to develop and assess the capability of future and current technologies to cost effectively and reliably address these issues. The results reported here are the outcome of the first in a series of evaluations to quantify the total and fine particulate emission control potential of modern, high efficiency electrostatic precipitators (ESPs) under EPRI project RP780 "Evaluation of High Efficiency Electrostatic Precipitators". Of particular interest in the program is characterization of well-maintained ESPs operating under optimum conditions as well as documenting off-design performance induced by normal day-to-day operating and maintenance problems. In addition to consideration of the emission control capabilities, these studies are also evaluating the economic, engineering and operational aspects of the ESPs. Although these latter considerations are frequently the governing factors in achieving acceptable performance, this paper will deal only with the emissions aspects. The reader is referred to the individual EPRI reports for more detailed information (Ensor, et al (1979)[1]).

PLANT DESCRIPTION

The data reported here were obtained at the George Neal Unit 3 ESP of Iowa Public Service Company, located on the Missouri River, 20 miles south of Sioux City, Iowa. The unit tested was a Foster Wheeler pulverized-coal fired boiler nominally rated at 520 Mw. Flue gas from the boiler enters a single economizer, splits into two separate ducting systems, and then enters an air preheater before passing through the ESP, I.D. fan and stack. At design conditions the total flue gas flow is 2,084,000 ACFM (300 °F and -20 in. H_2O) at the ESP outlet ducts. A diagram of the gas flow system is shown in Figure 1.

The fuel fired was a low-sulfur western subbituminous coal with a heating value of approximately 10,000 $^{btu}/lb$ and an ash content of 9-12%. A complete coal analysis as occured during the test period is given in Table 1.

The Neal Unit 3 has two precipitators (sides A and B) of European design operating in parallel with approximate size of 70 feet wide by 200 feet long. The ESPs were manufactured by Lodge-Cottrell and designed to achieve a removal efficiency of 99.7% at a specific collection area (SCA) of 880 $ft^2/kacfm$. Table 2 outlines the important ESP design features.

EXPERIMENTAL PROCEDURES

Field testing was performed simultaneously at the inlet and outlet of the "A" side of the ESP. Measurements included particulate size distributions from 0.02 to 10 micron diameter and opacity. Gas measurements of oxygen, sulfur dioxide, carbon monoxide and nitric oxide were also performed to monitor boiler operation. Description of the gaseous sampling system will be omitted, since it follows fairly well-established procedures and has no direct bearing on the results presented. A complete description of the sampling system is provided in Ensor et al (1979)[1].

Particulate Size Distribution

Particulate size distributions were obtained with cascade impactors and Electrical Aerozol Size Analyzers (EASA). The impactors provided size distribution information from nominally 0.5-20 micron particle diameter, and the EASA from nominally 0.02-0.8 micron particle diameter.

The impactor used in this study was a unit designed at Meteorology Research, Inc. (MRI) to facilitate sampling of particulate matter in stacks. The Model 1502 Inertial Cascade Impactor design is based on a simple annular arrangment of jets and collectors reported by Cohen and Montan (1967)[2]. There are seven stages with backup filter. Stainless steel foil discs coated with Apiezon-L grease were used to collect the particles.

The EASAs used were two model 3030 units manufactured by Thermo Systems, Inc. This instrument is currently the only practical commercially available instrument capable of measuring aerosol particle size distribution in the 0.01-to-1.0 micron diameter range. It was commercially introduced in 1973 and is a greatly improved version of the Model 3000 which was commercially introduced in 1967. The EASA is described in detail by Liu, Whitby, and Pui (1974)[3] and Liu and Pui (1975)[4].

It should be mentioned that the cross-sensitivity between many of the EASA particle diameter channels greatly affects interpretation of the data. A basic assumption behind the channel constants reported in the Thermo Systems, Inc., manual is that cross-sensitivity may be neglected. Use of the constants reported in the manual results in large errors when applied to narrow size distributions such as those often seen in combustion aerosols. Accordingly, in this work the EASA data were reduced with a number of different approaches to correct for cross sensitivity. The details of the data inversion method are presented in Ensor, et al (1979)[1].

Opacity

Measurement of opacity was conducted with two MRI Plant Process Visiometers (PPV). The instruments are based on light scattering theory and provide real-time monitoring of stack opacity as described by Ensor et al (1974)[5]. The large differences in inlet and outlet concentrations required full scale ranges in opacity of 97% and 7% respectively. In the present situation, opacity is defined as unity minus the light transmittance through the plume expressed as a percentage. The PPV allowed real-time measurement of opacity and recording of real-time events such as boiler upsets and precipitator rapping. This instrument was the sole measurement of opacity since the Neal station was not equipped with stack transmissometers.

RESULTS AND DISCUSSION

Introduction

To fully characterize the George Neal ESP emission control capabilities, a number of test conditions were examined. For example, the basic features of interest were the particulate matter mass collection efficiency and associated opacity at full load (520 Mw) under favorable electrical and mechanical conditions. The effects of ESP plate area (SCA) and rapping reentrainment on outlet emissions as well as particle size dependent collection efficiency are presented as a more in-depth examination of the ESP.

ESP Operation

The George Neal No. 3 ESP emission testing was performed in two distinct phases roughly five months apart. Although this approach reflects the prevailing EPRI philosophy of control device evaluation, several operating problems occured during the program which made the two test phase approach mandatory to insure representative data collection. The Phase I data were collected with a malfunctioning ash removal system and therefore are indicative of off-design operation. The Phase II data were collected following a unit outage for overhaul and are more representative of optimum ESP operation. Accordingly, the majority of the data presented will reflect the Phase II results. However, the Phase I results will be discussed when appropriate to illustrate the effect of operating problems on ESP performance.

Overall Particulate Mass Collection Efficiency

Total particulate mass collection efficiency data were collected at both full and partial loads of 520 and 303 Mw, respectively, as summarized in Table 3. The data are presented in several formats including penetration and collection efficiency. Penetration (defined as the outlet concentration ratioed to the inlet) is equivalent to unity minus collection efficiency. The use of penetration is useful because it is a more sensitive measure for very efficient collectors. For example, the difference in collection efficiency between 99.9% and 99% seems fairly small. In terms of penetration, however, the difference is 0.1% compared to 1%, or an order of magnitude.

To determine the effect of ESP plate area on particulate emissions, artificial variations in SCA were achieved by a combination of load reduction and deenergizing the last field. Although this approach does not absolutely isolate the effect of SCA as would different size ESPs operating at design conditions (due to effects of velocity distribution, residence time, etc.), it is believed that the observed trends described below are at least semiquantitatively correct.

As can be seen in Table 3, the overall collection efficiency ranges from 99.7 percent at a full load SCA of 745 ft^2/kacfm to 99.89 percent at a reduced load SCA of 1270 ft^2/kacfm. This performance exceeds the design specification of 99.7 percent at an SCA of 880 ft^2/kacfm. (The measured gas volumetric flow rate was about 10 to 15 percent greater than design). Also tabulated in Table 3 is the inlet flyash resistivity, which ranged from 2.5 - 5.0 x 10^{12} ohm-cm.

Examination of the full load data reveals total outlet emission levels of typically less than 0.025 lb/10^6 btu. The stack plume was slightly visible under these conditions, as suggested by the 4.6 percent stack opacity measured by the PPV. By comparison, the emissions are below the New Mexico particulate standard of 0.05 lb/10^6 btu total and 0.02 lb/10^6 Btu for particles less than 2 microns in diameter. In addition, these emission levels fall slightly below the revised New Source Performance Standard of 0.03 lb/10^6 btu recently promulgated by EPA.

There are two other effects of interest included in Table 3. First, with the given Neal flyash characteristics, it appears that an SCA in excess of 750 ft^2/kacfm is required to achieve a clear stack (opacity of 2-4 percent). Second, the fraction of particulate emissions less than 2 micron particle diameter ranges from 20-40 percent depending upon the specific operating condition. This fraction is larger than expected, as will be discussed later, and may in part explain the unusually high opacities observed at relatively large values of SCA.

Figure 2 gives a more graphical presentation of the data summarized in Table 3 and clearly illustrates the importance of SCA on emissions. It can be seen that significant improvements in collection efficiency by increasing plate area (SCA) may be confined to lower values of SCA. The "tailing off" of performance at higher SCAs may result from increasing dominance of non-ideal effects such as sneakage and velocity maldistribution. In terms of mass emissions it is interesting to note from Figure 1 that SCAs in excess of 700 ft^2/kacfm are required to achieve the EPA revised New Source Performance Standard of 0.03 lb/10^6 btu. Although these data are site-specific to Neal Unit 3, they do suggest a generic limitation of improving collection efficiency by increasing SCA alone. Other approaches such as improved electrics and sectionalization should b considered as possibly more cost effective options.

Also shown in Figure 2 is the effect on ESP performance of high ESP hopper ash levels due to a malfunctioning ash removal system. Note that the outlet emissions exibit a significant deterioration in performance during these episodes to roughly 0.08 lb/10^6 btu. This observed deterioration is believed to be due to the complex nature of the boiler/ESP/ash removal system, unavailability of critical monitoring instrumentation for plant operators, and the inherent difficulties associated with maintaining this equipment at peak performance. As a result, an emission level more representative of normal daily operation probably lies somewhere between 0.025 - 0.08 lb/10^6 btu.

It should be mentioned that problems with ash removal systems such as those observed at Neal are not uncommon in the utility industry and, in many cases, can be the "achilles heel" limiting performance of an otherwise well operating ESP. To address this issue, EPRI is currently conducting research project RP1401 "Reliability Assessment of Particulate Control Systems". The objectives are to develop a detailed data base documenting the major factors influencing control device reliability with emphasis on separating cause and effect and recommending appropriate improvements.

Size Dependent Collection Efficiency

Particle Size Distribution. Before the particle size dependent removal efficiency of the ESP can be determined, a careful measurement and interpretation of the particle size distribution entering and leaving the ESP is required. Previous experience has shown that the most useful method of presenting particle size distribution data is in terms of differential mass vs logarithmic particle diameter. When plotted on semi-logarithmic paper the area under the curve is proportional to the total mass. In addition, subtle features in the data become apparent which are not readily detectable in other formats such as cumulative mass vs particle size.

Figure 3 shows a typical ESP inlet differential mass distribution as a function of particle diameter measured under full-load conditions (520 Mw). The data above and below 0.3 microns diameter are EASA and cascade impactor results, respectively. The insert scale has been expanded by a factor of five to illustrate the noise estimation and overlap of data obtained with the two different instruments.

Figure 4 shows a typical ESP outlet differential mass distribution as a function of particle diameter measured simultaneously with the data shown in Figure 3. The ESP was operating under normal conditions with an SCA of 745 ft^2/kacfm. The cascade impactor data for diameters less than 1 micron are shown in both figures as dotted lines. These lines are the upper concentration limit, since examination by a scanning electron microscope (SEM) indicated some particle blowoff onto the two lower impactor stages. The cascade impactor data are the average of four runs in both figures, and the error bars indicate the standard deviation of the individual values, not the averages. The error bar on the peak of the submicron distribution indicates the variation in the average submicron concentration (assuming a variation in peak height). The agreement between the EASA and cascade impactor in the regions of overlapping data was good. The apparent differences although small on absolute basis may be due to blowoff in the impactor data and noise in the EASA data and inversion programs. The difference in the EASA and impactor data near 0.3 microns illustrates the difficulty in computing size distributions and penetrations in the 0.2 to 1 micron range. The EASA data were reduced with a number of different approaches to correct for cross-sensitivity as described in Ensor et al (1979)[1].

Bimodal Character of Distribution. The aerosol mass distribution has a distinctly bimodal nature as shown in Figures 3 and 4. A submicron mode is very sharp and distinct near 0.15 microns diameter and a second large particle mode is observed at 2 to 8 microns diameter.

The larger submicron peak in the outlet size distribution results from the inlet size distribution and size-selective removal of particulate matter by the ESP. The large particle mode is removed with much greater efficiency than the submicron mode as shown by comparing Figures 3 and 4.

The relative fraction of the submicron particle mode is typically 2 percent of the inlet total mass as determined by cascade impactors. The effect of reduced load is to reduce the relative fraction of submicron mode particulate matter. At the outlet of the precipitator, the amount of submicron particle mode is sensitive to the precipitator operation. Under normal conditions, the submicron mode is about 20 percent of the total outlet mass emissions.

The submicron particle mode was obvious only after the advanced data reduction techniques described in Ensor et al (1979)[1] had been used. The biomodal nature of the particle size distribution has been observed by the authors at other locations and may be a universal feature of coal combustion. A review of combustion-generated aerosol literature indicates that many investigators have not identified the submicron mode. This may be attributed to a failure to correct their EASA data for cross-channel sensitivity. The qualitative presence of a bimodal aerosol distribution with a submicron mode was reported by Ragaini and Ondov (1974)[6] with samples collected with filters and cascade impactors at the outlet of an electrostatic precipitator and subjected to SEM analysis. Schultz et al (1975)[7] observed particles approximately 0.1 micron in diameter collected on the last stage and final filter of cascade impactor samples which were "so uniformly sized" that they believed them to be condensed material. Follow-on research to further identify the submicron mode with respect to origin and chemical composition is currently being supported by EPRI.

Comparison to Aerosol Formation Theory. The inlet size distribution data were compared with the theoretical model reported by Flagan and Friedlander (1976)[8] as shown in Figure 5. The peak predicted by the model at 5×10^{14} particles/m^3 is approximately an order of magnitude larger than measured. However, the narrowness of the peak compares very favorably with the measured data. The theoretical model is based on a proposed mechanism in which part of the mineral content of the coal vaporizes and undergoes homogeneous condensation forming the submicron particle mode. According to this model, the submicron size mode may be expected to be enriched with volatile species. The remainder of the mineral material forms the fly ash mode at 2 to 8 microns and has a distribution shape similar to the initial pulverized coal size distribution. The agreement between the measured and theoretical number size distribution, though qualitative, is remarkable. The model was developed using data from the literature for the pulverized coal distribution and typical conditions of combustion. Possibly the agreement of theory and data would be better if the model was refined to match the subject boiler.

Penetration as a Function of Diameter. Size-dependent penetration is the outlet aerosol distribution divided by the inlet distribution, with both distributions as functions of particle diameter. Penetration results for the three SCA conditions tested are shown in Figure 6. Penetration greater than 0.3 microns is based on cascade impactor data; penetration less than 0.2 microns is based on EASA data.

It can be seen from Figure 6 that a double peaked (bimodal) penetration behavior is prevalent under all test conditions. Near design (SCA of 745 ft^2/kacfm), penetration peaks of 10 and 5 percent are evident at 0.2 and 1.0 micron, respectively. In addition, the submicron mode penetration is observed to be about thirty times the overall ESP penetration. Even at extremely large values of SCA (1270 ft^2/kacfm), the bimodal characteristic is preserved despite the high overall collection efficiency of 99.89 percent.

The large penetration at 0.2 micron can be qualitatively explained by physical arguments. Hewitt (1956)[9] reported a fundamental laboratory and theoretical study of electrostatic precipitation. His data were recently reproduced by Smith et al (1978)[10]. The minimum particle mobility (or migration velocity) was found at a particle diameter of 0.2 microns. Thus, the 0.2 micron particles would be expected to have the lowest collection efficiency or highest penetration of the particles entering the precipitator. The penetration of particles less than 0.2 microns in diameter decreases with a reduction in particle diameter, because of the increasing significance of diffusion charging and Brownian and turbulent migration. The penetration of particles greater than 0.2 microns in diameter decreases with increasing particle diameter because of the increased effect of field charging and increased migration velocities. The submicron particle mode was at the point of minimum mobility or efficiency as reported by Hewitt. Thus, the penetration of the submicron mode was much higher than the total mass penetration. However, the submicron mode penetration is much larger than expected by consideration of only particle mobilities.

It has been assumed in this analysis that a continuous curve joins the EASA and cascade impactor data as indicated by the dashed lines without error bounds. The steep increase of the penetration near 0.13 micron and the dropping penetration below 1.0 micron forces a sharp peak in penetration between 0.18 and 0.25 micron. The peak is sufficiently sharp to cast some doubt on its reality because a smoother curve was expected as reported by Hewitt. The sharp submicron distributions make penetration calculations very sensitive to error, and the blowoff in the lower cascade impactor stages may create an anomalous drop below 1.0 micron. This phenomenon unfortunately lies in the region in which both the EASA and impactor data are least reliable. This uncertainty is due in part simply to the relative scarcity of aerosol between 0.2 and 1.0 microns in the flue gas. Accordingly, the "true" curves may more closely resembly a smooth line joining the squares at 0.13 microns with the cascade impactor data at 1 micron.

There are several possible explanations for the large penetration of submicron particles and the double peaked penetration curve as discussed below:

- Experimental problems inherent with the measurement techniques. Most of the problems have been described above and in Ensor et al (1979)[1]. However, the use of matched EASAs, extensive data inversions, SEM micrographs of filters and impactor stages, and the reproducibility of the data stongly suggest that the results are real.

- The high resistivity ash caused the ESP to operate in an extreme back corona condition. The effect on particle charging and collection under these conditions is not completely understood at the present time.

- The possibility exists that the high penetration of submicron particles is fictitious in the sense that it is influenced by agglomeration. However, the agglomeration would have to take place between the 0.13 to 0.3 micron particles because agglomeration between 0.13 and larger particles would have reduced penetration of the submicron particle mode. There is some evidence to support the presence of this mechanism. Comparing Figures 3 and 4 indicates that the distribution peak increased in mean diameter by about 0.05 microns from the inlet to the outlet of the ESP. The highly charged aerosol may have grown through coagulation during the 25-second residence time in the ESP. The penetration is very sensitive to small changes in the submicron particle mode because of the sharpness of the distribution. The small shift in the outlet submicron particle mode was towards the "valley" between the inlet size distribution modes. Thus, the large penetration calculated for the 0.15 to 0.3 micron particle range may result from a submicron particle growth rather than precipitation.

In summary, although the exact mechanisms responsible are not well understood, the bimodal aerosol inlet distribution and the subsequent double peaked penetration curve in the fine particle region (less than 2 microns in diameter) appears to be real and present under all test conditions.

Rapping Losses

When an ESP collection plate is rapped to remove the layer of accumulated ash, some of the ash is reentrained by the gas stream. These emissions are called rapping losses. The loss of particles appears to result from two mechanisms: 1) the fracturing of the layer of ash from the plates immediately after the rap, and 2) "boilup" of ash from the hoppers as the sheets of dislodged ash reach the ash in the hoppers.

The primary experimental technique used to investigate rapping losses were tests conducted with the rappers on and off similar to the techniques described by Gooch and Piulle (1977)[10]. The sampling approach was to position two sets of two impactor probes at the outlet of the precipitator. One set was used to sample emission during a half-hour operation with the rappers on and the other was used during the half-hour when all rappers were shut off. The EASA, PPV, inlet impactors, and gas monitors were operated normally. The hoppers were all emptied about two hours before the testing was started to reduce the likelihood of excessive "boilup" emission because of high hopper levels.

A limitation of this test approach is the distortion of the operation of the ESP. During the rappers-off tests, layers of ash on the plates may build to an excessive depth, resulting in particle losses due to erosion by the gas stream. This excessive buildup may be significant only on the inlet fields. The outlet fields performance could then be affected by the ash losses from the inlet fields.

Based upon comparison of data from two sets of rappers-on and-off tests, it is estimated that rapping losses account for roughly six percent of the outlet emissions. However, statistical analysis of the results reveals no significant difference between the rapper-on and -off tests, thus suggesting that the differences measured may have been obtained by chance.

The small difference between the rap and no-rap operating conditions was substantiated by the outlet PPV opacity measurements. The rapping puffs in opacity reported by other investigators, given in Gooch et al (1975)[11], were not obvious during the test. However, it should be mentioned that significant rapping puffs were observed in the outlet opacity measurements during times of high ash hopper levels. This result suggests that ash hopper level may be a significant parameter affecting the absolute level of rapping losses, at least for ESPs of European-design. Details of the rappers-on and-off tests are given in Ensor et al (1979)[1].

CONCLUSION

Test results for the Neal ESP indicate that high particulate removal efficiencies are possible with large ESPs collecting high resistivity flyash. For example, outlet emissions of 0.025 $^{lb}/10^6$ btu were measured at full load conditions of 745 ft^2/kacfm, below the revised EPA New Source Performance Standard (NSPS) of 0.03 $^{lb}/10^6$ btu. However, these results must be tempered by the fact that the data were collected from a well tuned ESP shortly after overhaul. In contrast, emission levels measured prior to overhaul revealed a significant deterioration in performance to roughly 0.08 $^{lb}/10^6$. This observed deterioration is believed to be due to the complex nature of the boiler/ESP/ash removal systems, unavailability of critical monitoring instrumentation, and the inherent difficulties associated with maintaining this equipment at peak performance. Accordingly, an emission level more representative of normal daily operation probably lies somewhere between 0.025-0.08 $^{lb}/10^6$ btu.

Examination of the particulate size distribution revealed that the ESP inlet aerosol has a distinctly bimodal nature, i.e. the particle mass is concentrated in two distinct size regions: a submicron mode at 0.15 microns and a large particle mode at 2 to 8 micron diameter. This bimodal nature propagates through the ESP resulting in a bimodal penetration behavior not previously reported. The submicron aerosol mode penetration averages 10 percent at full load, or about 30 times the overall ESP penetration. In terms of total mass, the sub-2 micron particles account for 20 - 40 percent of the total outlet emission. The implications of the high submicron penetration are presently unclear, although it may be responsible for the relatively high stack opacities observed at correspondingly large values of SCA.

If it is assumed that emission standards more stringent than those currently in effect will be promulgated, then it is clear that sufficient cushion must be provided in the ESP design to account for operational excursions and the seemingly time dependent deterioration in performance. However, the most cost effective methods to achieve this cushion are not obvious. Adding plate area is one option used extensively in the past, although the results presented here show that the proportional gains in performance diminish rapidly at large values of SCA. Therefore, to retain ESPs as a viable alternative for the utility industry it appears that advancements in ESP systems will be required. Several such alternatives are currently under development both by EPRI and independent research organizations.

ACKNOWLEDGEMENTS

The permission to test the George Neal Unit No. 3 by Iowa Public Service is gratefully acknowledged. The assistance by G. Spooner and J. Hardie during the test is appreciated. A special thanks to MRI personnel including G. Markowski, M. Murphy, S. Muller, R. Hillestad, M. Drehsen and L. Knoll. The technical support by J. Ebrey and D. Cook of Lodge-Cottrell, Inc. during the study is appreciated.

REFERENCES

1. Ensor et al. "Evaluation of the George Neal Electrostatic Precipitator". EPRI Final Report RP780-1, Volume I
2. Cohen, J.J., and D.M. Montan. "Theoretical Consideration, Design and Evaluation of a Cascade Impactor". Am. Ind. Hyg. Assoc., Vol. 28, 1967 PP. 95-104
3. Liu, B.Y.H., K.T. Whitby, and D.Y.H. Pui. "A Portable Electrical Analyzer for Size Distribution Measurement of Submicron Aerosols." J. Air Poll. Cont. Assoc., Vol. 24, 1974, p. 1067
4. Liu, B.Y.H., and D.Y.H. Pui. "On the Performance of the Electrical Aerosol Analyzer." J. Aerosol Sci., Vol. 6, 1975, p. 249.
5. Ensor, D.S., L.D. Bevan, and G. Markowski. "Application of Nephelometry to the Monitoring of Air Pollution Sources". In Proceedings of the 67th Annual Meeting of the Air Pollution Control Association, Denver, June, 1974. Paper No. 74-110.
6. Ragaini, R.C., and J.M. Ondov. "Trace Contaminants from Coal-Fired Power Plants." In Proceedings of the International Conference of Environmental Sensing and Assessment, Las Vegas, September 14-19, 1975.
7. Schultz, E.J., R.B. Engdahl, and T.T. Frankenburg. "Submicron Particles from a Pulverized-Coal-Fired Boiler." J. Atmos. Environ., Vol. 9, 1975, p. 111.
8. Flagan R.C., and S.K. Friedlander, "Particle Formation in Pulverized Coal Combustion - A Review." In Proceedings of the Symposium on Aerosol Science and Technology at the 82nd National Meeting of the American Institute of Chemical Engineers, Atlantic City, New Jersey, August 29 - Sept. 1, 1976.
9. Hewitt, G.W. "The Charging of Small Particles for Electrostatic Precipitation". AIEE Paper 56-353, New York, 1956.
10. Smith, W.B., et al. "Experimental Investigations of Fine Particle Charging by Unipolar Ions--A Review." J. Aerosol Sci., Vol. 9, 1978, pp. 101-124
11. Gooch, J.P., and W. Piulle, "Studies of Particle Reentrainment Resulting from Electrode Rapping." Proceedings: Particulate Collection Problems Using ESPs in the Metallurgical Industry. EPA Report No. 600/2-77-208, October, 1977, pp. 103-128.
12. Gooch, J.P., and N.L. Francis. "A Theoretically Based Mathematical Model for Calculation of Electrostatic Precipitator Performance." J. Air Poll. Cont. Assoc., Vol. 25, 1975, pp. 108-113.

TABLE I
NEAL COAL ANALYSIS

	Mean Percent	Standard Deviation
Coal Proximate Analysis		
Moisture	12.66	0.905
Ash	10.62	1.3
Volatile Matter	35.96	1.1
Fixed Carbon	40.75	1.03
Sulfur	0.61	0.19
Heat Value*	10,011*	181*
Coal Ultimate Analysis		
Carbon	65.76	1.2
Hydrogen	4.93	0.17
Nitrogen	1.12	0.012
Chlorine	0.00	0.0
Oxygen	15.33	0.39
Coal Mineral Analysis		
SiO_2	44.6	3.0
Al_2O_3	17.4	0.93
Fe_2O_3	5.72	2.5
Na_2O	0.33	0.065
K_2O	1.13	0.21
CaO	16.1	1.7
MgO	2.8	0.26
TiO_2	0.78	0.14
P_2O_5	0.92	0.14
SO_3	8.7	2.4

Fifteen coal samples from five coal feeders at three different times

* - Heat Value units are Btu/lb

Table 2

DESIGN FEATURES, NEAL No. 3 ELECTROSTATIC PRECIPITATORS

	Design	Range
Gas volume (acfm)	2,084,000	1,026,000 to 2,084,000
Gas velocity through ESP (FPS)	2.26	
Treatment time (Sec.)	26.5	

	Quantity
Number of chambers per precipitator	One (two per boiler)
Number of cells per precipitator	Eight (sixteen per boiler)
Number of electrical fields per precipitator	Four
Bus section per field	Eight
per precipitator	Thirty-two
per boiler	Sixty-four
Number of T-R sets per bus section	1/2
Number of T-R sets per field	4
Number of T-R set per precipitator	16
Collecting Plates	ASTM A-36, 18 GA.
Number of gas passages per bus section	24
Number of plates per field	
a. Field 1	196 per ESP
b. Field 2	196 per ESP
c. Field 3	196 per ESP
d. Field 4	196 per ESP
Total	784 per ESP
	1568 per boiler
Active plate area (does not include stiffeners)	921,600 ft^2 per ESP 1,843,200 ft^2 per boiler

Table 3

Summary of Collection Efficiencies for "A"
ESP Under Various Operating Conditions

Test Conditions	*Load (MW)*	*SCA (ft^2/kacfm)(a) [m^2/(m^3/sec)]*	*Average Inlet Resistivity (ohm-cm)*	*Total Corona Power (kW)*	*Average Inlet Concentration(b) (gr/scf) [g/m^3]*	*Average Outlet Concentration(b) (gr/scf) [g/m^3]*	*Efficiency (percent)*	*Penetration*	*Opacity(c) (percent)*	*Total Emissions (lb/10^6 Btu)*	*Less Than 2 Microns(d) (lb/10^6 Btu)*
Partial load	303	1270 [250]	2.5×10^{12}	415	2.35 [5.38]	0.00265 [0.00607]	99.89	0.0011	1.6	0.005	0.001
Full load	522	745 [147]	4.0×10^{12}	330	3.30 [7.56]	0.0101 [0.0231]	99.70	0.0030	4.6	0.019	0.009
Rappers on(e)	520	740 [146]	5.0×10^{12}	300	2.55 [5.84]	0.0129 [0.0295]	99.49	0.0051	5.2	0.024	0.011
Rappers off(e)	520	740 [146]	5.0×10^{12}	300	2.55 [5.84]	0.0122 [0.0279]	99.52	0.0048	5.0	0.023	0.009
Last field deenergized	523	550 [108]	4.0×10^{12}	215	2.95 [6.76]	0.0305 [0.0698]	98.97	0.0103	12.7	0.057	0.027

Note: This table does not contain the tests during episodes of mechanical and electrical malfunctions. The SCA's were computed using velocity traverse data and the outlet emissions lb/10^6 Btu calculated using the EPA "F" factor method.

(a) Actual volumetric flow rate

(b) Standard conditions: 21.1°C, 76 cm Hg dry

(c) Corrected to 6.9-meter path length corresponding to the top of the stack

(d) Actual diameter with a density of 2.6 g/cm^3

(e) Rappers turned off for 30 minutes every hour

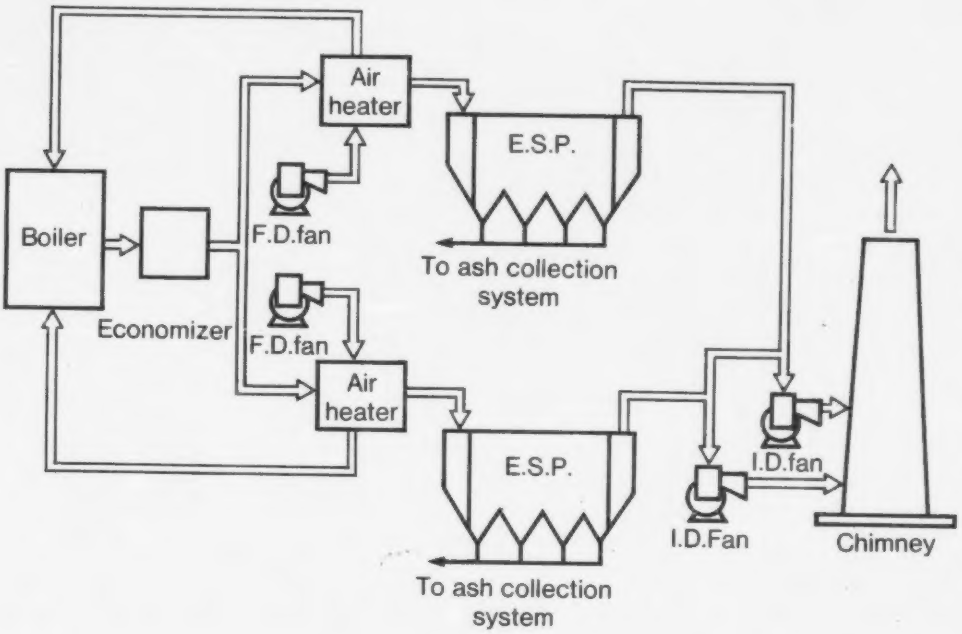

Figure 1. Gas flow diagram for Neal Unit No. 3.

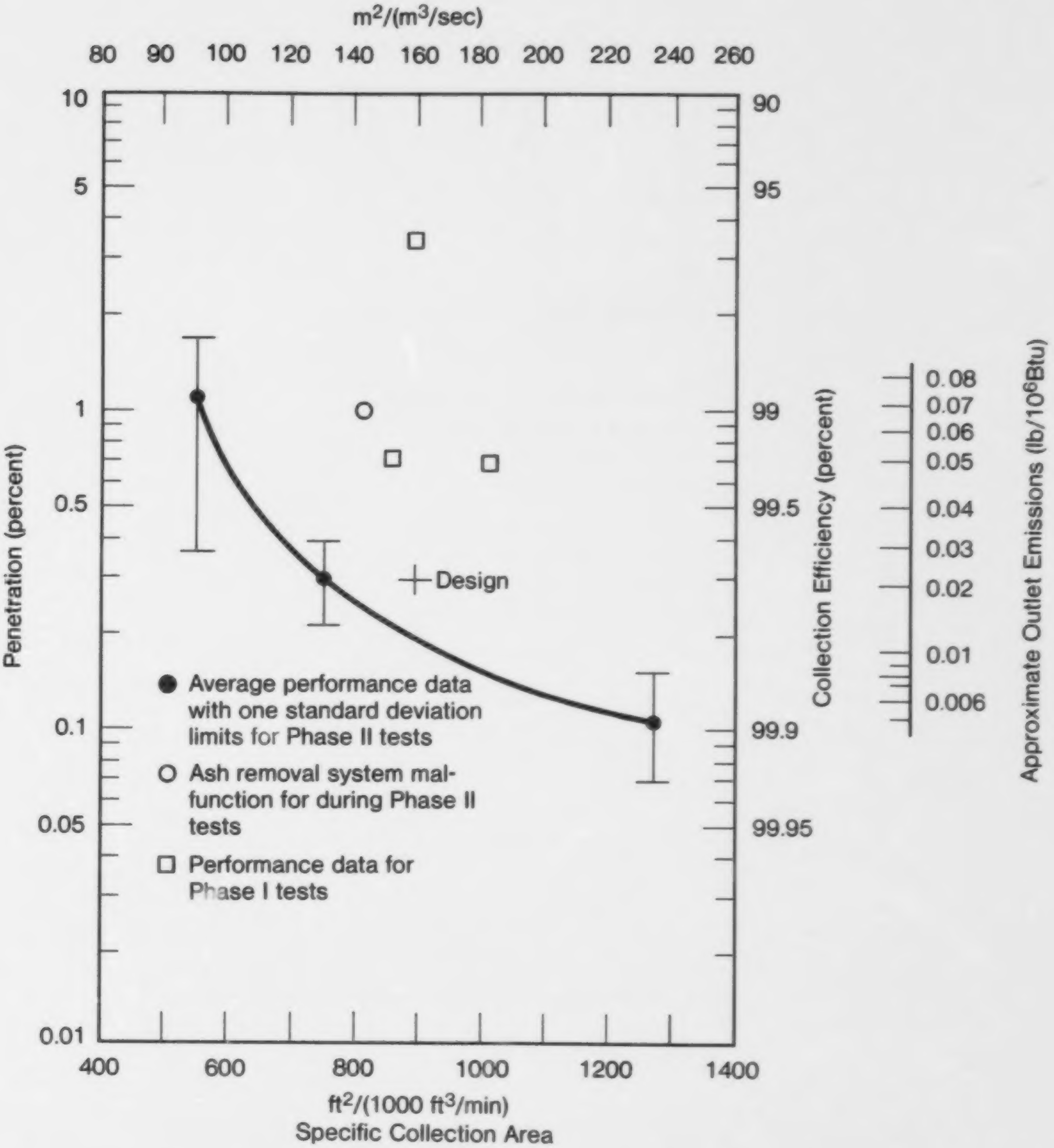

Figure 2. ESP performance as a function of specific collection area.

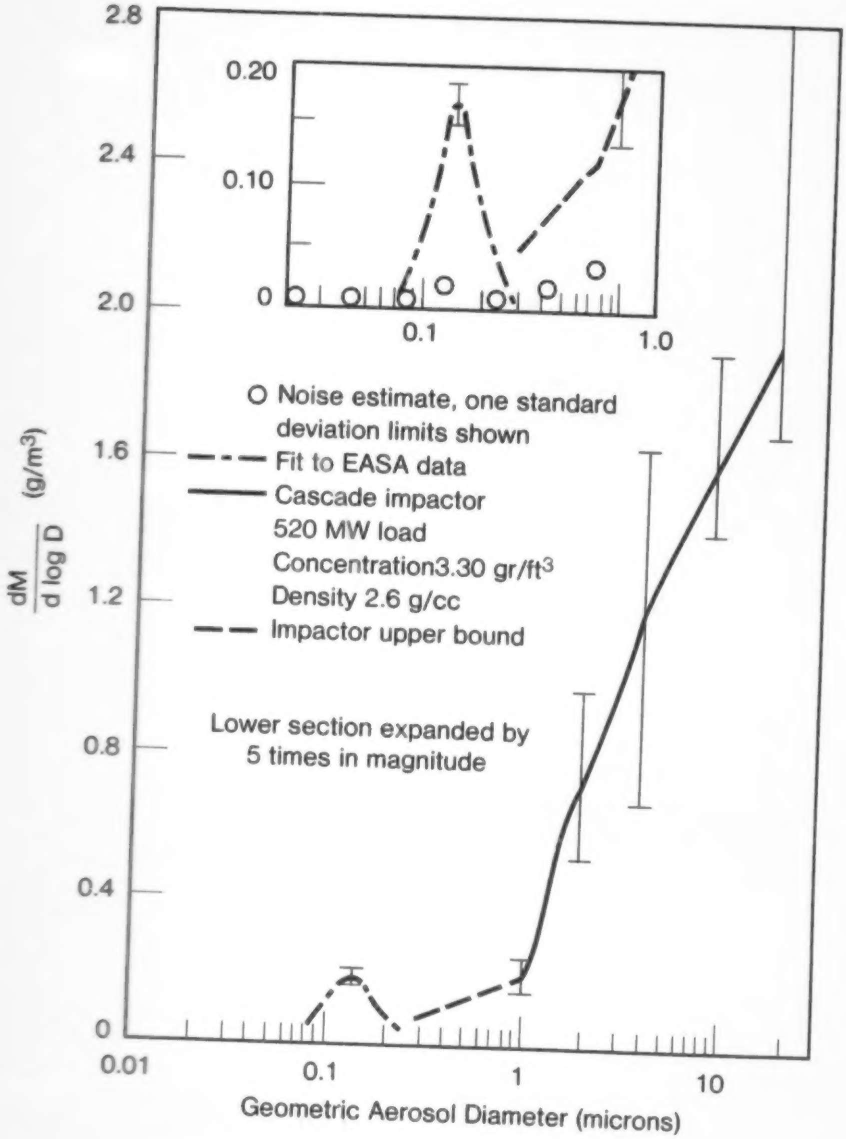

Figure 3. Differential mass particle size distribution at the inlet of the ESP.

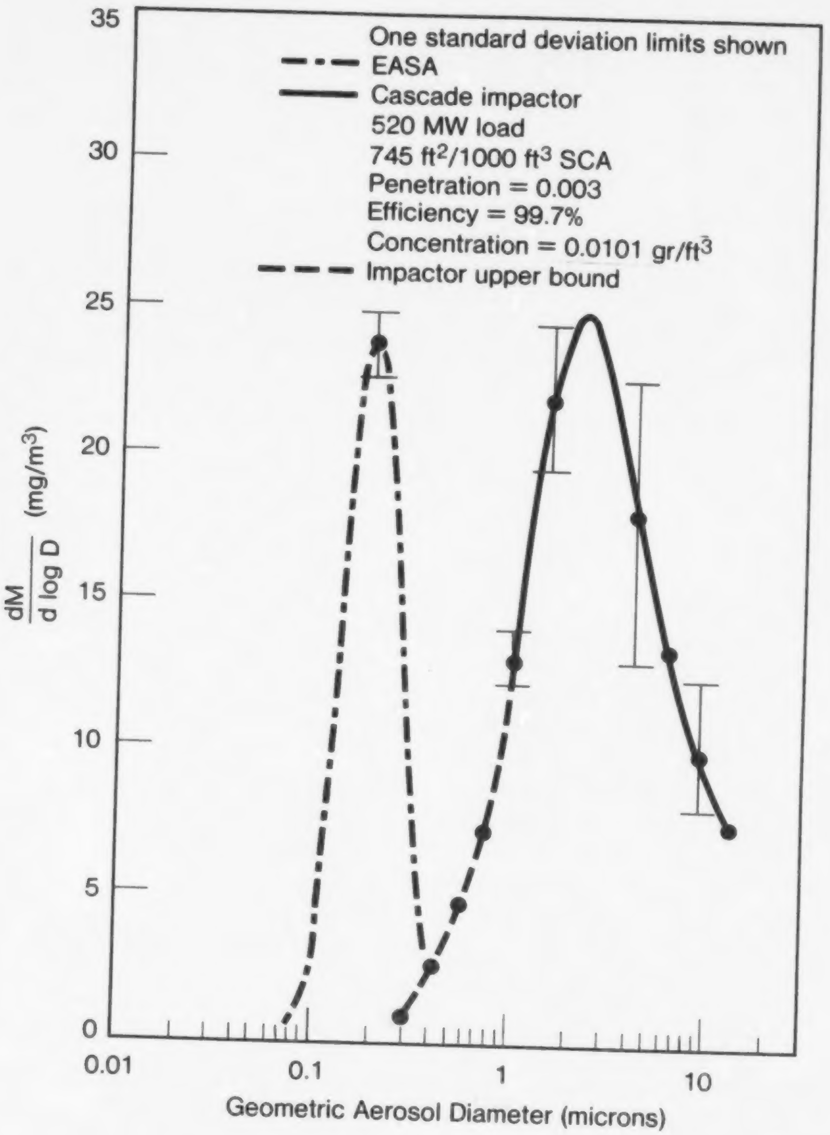

Figure 4. Differential mass particle size distribution at the outlet of the ESP

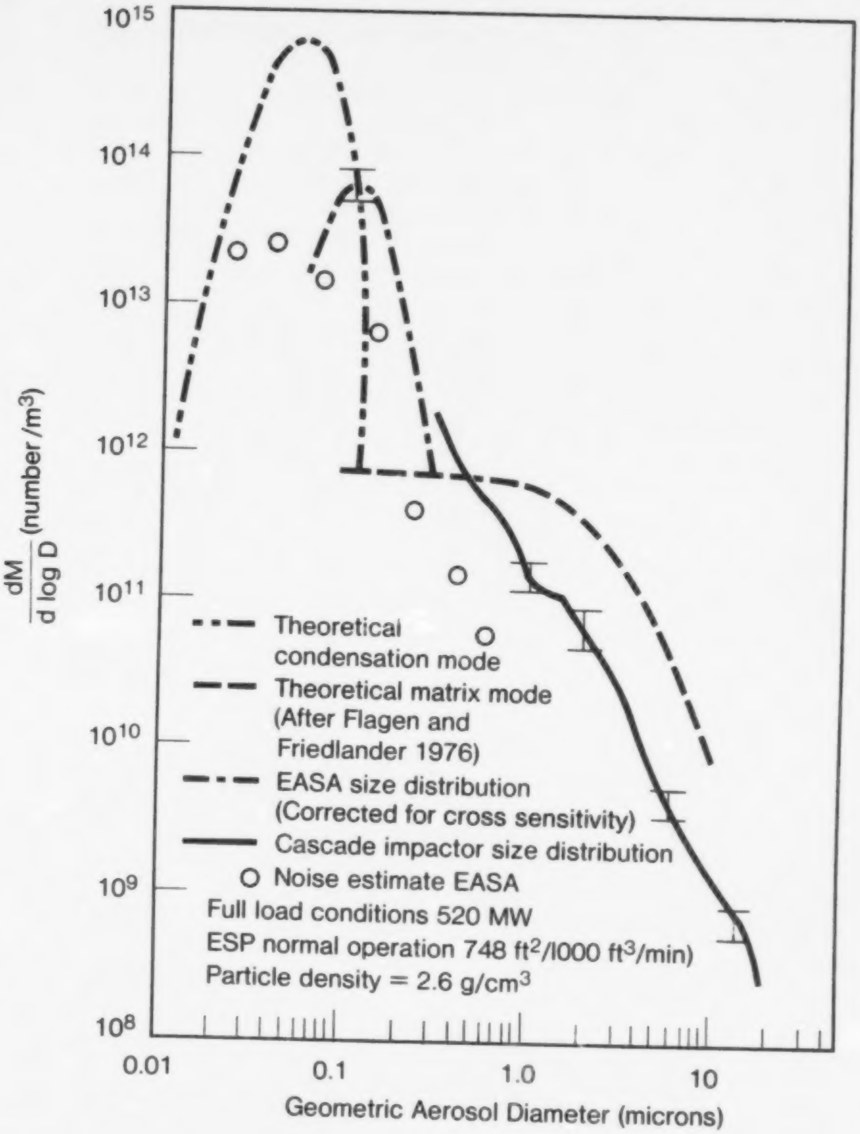

Figure 5. Comparison of inlet differential number size distribution to the theoretical distribution reported by Flagen and Friedlander (1976) for the combustion of pulverized coal.

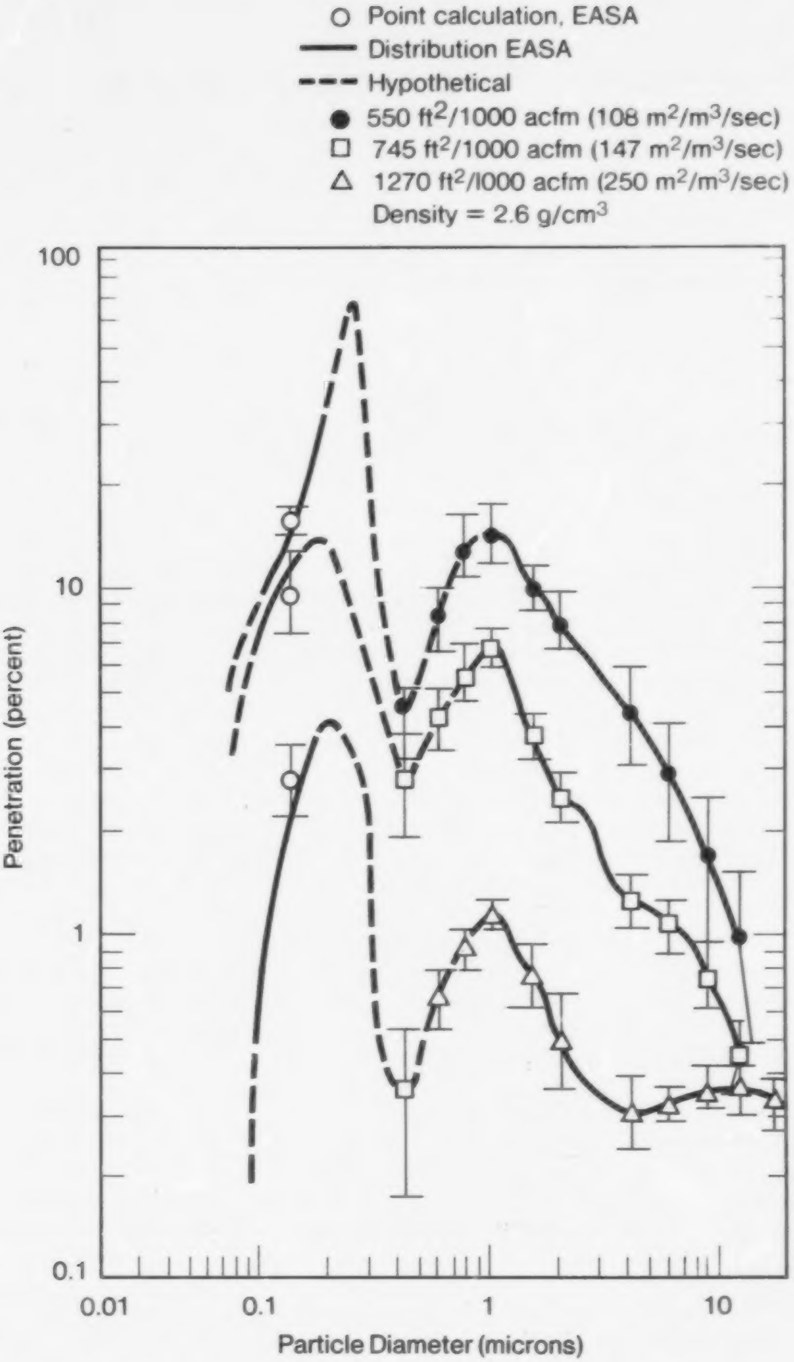

Figure 6. Penetration and collection efficiency as a function of particle diameter for three specific collection areas.

EPA MOBILE ESP HOT-SIDE PERFORMANCE EVALUATION

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ABSTRACT

This report describes the Environmental Protection Agency mobile electrostatic precipitator performance evaluation conducted at the Navajo Generating Station, Page, Arizona. The objective was to evaluate discrete process and control device parameters in order to effect improved collection performance of a hot-side electrostatic precipitator applied to a western-coal-fired utility boiler. The pilot-scale electrostatic precipitator was operated in a hot-side mode, slipstreaming flue gas upstream of the air preheater and full-scale hot electrostatic precipitator. Performance measurements on the pilot unit were conducted over a 3 month period in order to study the effects of dust layer characteristics, temperature/boiler load conditions, and sodium carbonate conditioning. A time-dependent degradation in collection performance was observed in the pilot model, as evidenced in the full-scale models. Sodium conditioning effected a substantial improvement in collection performance, eliminating the time-dependent degradation pheonomenon. Use of mathematical performance models provided a reasonable reference for data interpretation, as well as insight into the hot precipitation problem.

INTRODUCTION AND OBJECTIVE

This pilot-scale electrostatic precipitator (ESP) is one of three conventional particulate emission control devices mobilized by the Utilities and Industrial Power Division, Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency (UIPD/IERL/EPA), Research Triangle Park, North Carolina. The objective is to evaluate and compare the performance characteristics of a pilot scale electrostatic precipitator, scrubber, and baghouse on industrial particulate emission sources. The purpose is to provide characteristic information and insight for appropriate selection of particulate control devices, in light of operation, performance, and cost considerations.

Hot-side precipitation has recently evolved as a cost- and technology-effective means for particulate control from low sulfur coal-fired utility boilers. Several low sulfur coals produce high resistivity fly ash, causing dramatic increases in costs for cold-side ESP control. The hot-side approach utilizes thermal conditioning of the fly ash to reduce resistivity. By positioning the ESP to the hot-side of the air preheater, the resultant increase in gas temperature from 170°C to 370°C typically reduces fly ash resistivity by 2 to 3 orders of magnitude. However, certain hot-sided ESP's have demonstrated a time-dependent performance degradation, with evidence of electrical breakdown of the collected fly ash. Such characteristics have been observed at the Navajo Station, prompting a cooperative effort to investigate this phenomenon between the Salt River Project and IERL/EPA. An evaluation of the full-scale ESP performance was conducted by Southern Research Institute (SRI).[1] Further investigation has been conducted by Acurex with the EPA pilot-scale ESP.

This report summarizes the results of the EPA mobile ESP performance evaluation at the Navajo Station during the summer of 1978. The mobile ESP treated an isokinetically removed slipstream over a temperature range of 230°C to 330°C. Particulate concentration and size distribution measurements were conducted daily on the influent and effluent streams of the pilot unit. Boiler and ESP operating data were collected, along with fly ash samples. Dry sodium carbonate was injected to evaluate conditioning effects. Performance levels and trends are included in this report, along with analytical discussions on operating and particulate data, fly ash composition, and means of data reduction and interpretation.

CONCLUSIONS

The following conclusions result from this study:

- Several ESP behavior characteristics indicate breakdown of the collected fly ash during normal operation
- Electrical breakdown severely limits collection performance
- Sodium conditioning alleviates breakdown and performance limitations by favorably reducing base/sodium ratio
- Sodium conditioning reduces emission levels by an order of magnitude--from ∿300 to 30 ng/J for SCA of ∿90 m^2/m^3/sec (from ∿0.7 to 0.07 lb/million Btu for SCA of ∿450 ft^2/kcfm)
- Substandard pressure conditions adversely affect hot precipitation of low alkali, low sulfur western coals.

DESCRIPTION OF FACILITIES

Test Site

Navajo Generating Station is owned and operated by the Salt River Project. It consists of three 800 MWe pulverized coal-fired boilers. They were completed from 1974-1976 and represent current design and operating methodology. Emissions are controlled by hot-side electrostatic precipitators, located upstream of the air preheaters (340-380°C) instead of in the conventional downstream location (150-180°C). The flue gas characteristics at the ESP location were:

Temperature Range:	290-370°C
Particulate Concentration:	9.3 gm/DSCM
Specific Resistivity:	4×10^9 ohm-cm @ 350°C

• CO_2	14.5-15.0% v/v
• O_2	4.5- 5.0% v/v
• H_2O -	9.0-10.0% v/v
• SO_2	450-500 ppm

Pilot ESP

The EPA mobile ESP consists of two separate units mounted on 12.2 m freight trailers. One unit is the process trailer, which houses a five-section electrostatic precipitator and the following auxiliary equipment:

- Flow rectification devices (vaned turning elbows and diffusers)
- An induced-draft fan with cooling system for 540°C service
- A screw conveyor and rotary airlock for fly ash removal
- Electromagnetic plate vibrators and pneumatic corona frame rappers
- Five transformer rectifier units (each rated at 50 kV, 15mA DC)

The system is designed to handle 28-85 m^3/min at 540°C maximum.

The other unit is a control/laboratory trailer containing all process instrumentation and controls, analytical laboratory equipment, and spare equipment storage. A more complete description of the EPA mobile ESP is presented in Reference 2.

A comparison of pilot- and full-scale ESP design and operating specifications is shown in Table 1.

PROGRAM METHODOLOGY

Installation

The mobile ESP trailers were placed on the north side of Unit No. 1. The slipstream probe was installed in the ductwork between the boiler and the air preheater at a point of sufficiently isokinetic velocity. The duct ran 14 m horizontally and 35 m vertically to the mobile ESP. The vertical section was supported by a spring hanger to allow for thermal expansion. The duct was electrically heat traced and insulated. Heat losses in the slipsteam limited the temperature range of this evaluation.

Operation

The tests were conducted in increments of 4 to 5 days, with the mobile ESP operating continuously during those periods. Precipitator performance as a function of operating time could thus be observed. All internal precipitator components were cleaned of fly ash before the initial operating period. In order to observe the cumulative effects of dust layer buildup, normal wire and plate cleaning patterns were employed for collected ash removal. Corona wire and plate rapping cycles were not interrupted during sampling in order that rapping losses be included in the precipitator performance evaluation.

Test Conditions

The mobile ESP tests were performed in phases as described below:

Phase I

The first 11 tests were conducted between June 7 and June 23. Operational problems with the duct heaters resulted in an average inlet gas temperature of 260°C, well below the 340-370°C range of the full-scale ESP.

Phase II

After a 2-week shutdown period for heater repairs, 15 more tests were conducted between July 11 and August 3. Average operating temperature was 295°C.

Phase III A

Five tests were conducted between August 8 and August 14. Sodium carbonate was injected upstream from the pilot ESP as a conditioning agent. The average concentration injected was 8.16 percent as Na_2O, expressed as a mass fraction of fly ash. Average operating temperature was 295°C.

Phase III B

The boiler output dropped to half-load and remained there from August 22 to 25. Four tests were conducted. Average sodium carbonate injection was 2.33 percent as Na_2O, and the operating temperature dropped to 245°C due to reduced boiler load.

Table 2 summarizes the test conditions and analytical results.

Data Acquisition

The following pilot ESP data were recorded semihourly throughout the program:

- Inlet and outlet gas temperature
- Slipstream interface temperature
- Individual secondary voltages
- Individual secondary currents

Corona current as a function of voltage were recorded daily and plotted (corona discharge curves). Dust layer thickness measurements were made periodically at the beginning of the program but were discontinued due to the long off-line and reheat time requirements.

Pertinent boiler operating data were recorded hourly in the control room. Copies of the logs were made available for all test days. Operating points of selected plant ESP cells were also recorded.

Flue gas composition and velocity data were recorded daily as a part of particulate sampling preparation. Filter and impactor stage weight data were obtained in the field using the mobile laboratory, and were usually available within 2 days of a given test.

Particulate Measurements

Particulate loading and particle size distribution were determined with a Brink impactor at the pilot ESP inlet and with a University of Washington Mark III impactor at the outlet. Each impactor train was operated in conjunction with a modified EPA Method 5 train using a 47 mm glass fiber filter as a comparison and quality control check. All filters and impactor substrates were made of Reeve Angel 934AH glass fiber. Filter preconditioning was not performed due to the low sulfur content of the flue gas.

Data Reduction

Several analytical tools were employed in the reduction and analysis of particulate concentration and size distribution data. The large number of particulate tests (concentration: 130; size distribution: 120) taken over a variety of conditions for 35 test days required a substantial analytical effort.

A computer program was used to calculate impactor stage cut-points and dust loadings. Fractional penetrations were calculated using a program that performs the following:[3]

- Log-normal transformation of inlet and outlet cumulative size distributions
- Linear, quadratic, and spline fits to the transformed data
- Analytical differentiation of the fitted curve
- Calculation of fractional penetrations from differential inlet and outlet size distributions

Performance of the ESP was evaluated using the performance model developed by SRI.[4] In view of the fact that the model overpredicts penetration to a large extent and that V-I data do not conform to the predictions, only a moderate modeling effort was made.

The pilot ESP tests were conducted at different SCAs to evaluate the effect of specific collection area (SCA) on particulate emissions. However, performance results require adjustment to a common SCA to evaluate the effects on a common design basis. This was accomplished by the use of two ESP performance equations:

1. Deutsch-Anderson (D-A) Equation

   This equation relates efficiency (n) to SCA and particle migration velocity (w) by the equation

   $$n = 1 - e^{-(SCA \cdot w)}$$

   Using measured efficiency and SCA for a given test, $\underline{w}$ can be calculated with the above equation. Assuming $\underline{w}$ to be constant for small variations in SCA, efficiency can then be calculated for the desired common SCA by applying the above equation.

2. Matts-Ohnfeldt (M-O) Equation

   Matts and Ohnfeldt have determined empirically that the following relationship describes the ESP performance better than the Deutsch-Anderson equation:[5]

   $$n = 1 - e^{-(w \cdot SCA)^{0.5}}$$

   This equation can similarly be used to adjust efficiency data to a common SCA.

Australian experience with electrostatic precipitation technology has shown that ESP performance can be described by extending the Deutsch-Anderson equation as shown:[6]

$$\ln(1-n) = \ln(1-n_o) + C(SCA \cdot V^2)$$

Where n_o is the mechanical efficiency, V is the applied voltage, and C is a constant. The first term accounts for mechanical settling, and the second one restates the Deutsch-Anderson equation by relating voltage and migration velocity. Theoretically a semilog plot of penetration (1-n) vs. $SCA \cdot V^2$ gives a straight line relationship. In actuality the ESP performance plots a line as shown in Figure 1. Leveling-off of the performance line at high values of $SCA.V^2$ is due to reentrainment losses. In similar fashion, the M-O equation can be extended. The abscissa in this case is $(SCA \cdot V^2)^{0.5}$ instead of $SCA \cdot V^2$.

RESULTS AND DISCUSSION

This program was directed to study hot ESP performance limitations at the Navajo Power Station and to assess alternate means for improved performance.

The fundamental cause of the limitation appears to be excessive resistivity due to relatively low sodium levels. Use of an in situ resistivity probe would have documented real-time and possible time-dependent resistivity levels. Nonetheless, test results with laboratory resistivity values have provided additional understanding into the character of hot precipitation. A discussion of the results follows, describing and relating pilot precipitator behavior characteristics under a variety of conditions.

Summary of Pilot ESP Performance

Analytical and graphic accounting for the 35 days of pilot ESP performance is detailed and depicted in Table 2 and Figure 2, respectively. Collection performance trends are observed in Figure 2 as the series of test days are segregated in week-to-week increments. Outlet loadings increase as the pilot ESP operation and performance levels degrade with elapsed on-line time (0-4 days) for the first 7 test weeks. During this period (Phase I and II), the pilot precipitator was treating a representative slipstream at half-load temperature levels. The last two data series in Figure 2 show a trend of performance enhancement. During this period (Phase III), sodium conditioning by dry injection into the slipstream effected a dramatic improvement in collection performance. Virtual restoration of clean-plate performance was effected by sodium conditioning, as the performance levels on the first and last test days approach the same value of 0.07 gm/DNCM. Results of chemical analyses of 30 samples support the conclusion that performance improvements were directly associated with sodium content levels.

The extent of hot-side performance improvement associated with sodium conditioning is more appropriate and dramatic as steady-state conditions are described (Figure 3). An approximation of steady-state performance was formed by extrapolation of transient profiles to depict a more respresentative comparison. A 80-90 percent reduction in emission level is supported by the improvement levels resultant from sodium conditioning at the Commanche Station of Public Service Company of Colorado.[7]

Summary of Precipitator Operation Characteristics

Operating corona points and the associated corona discharge relationships (V-I data) were taken regularly during the program. Manual control of the transformer-rectifier was conducted, since the pilot facility was not equipped with automatic controllers customarily included in full-sized precipitators. Operating points were set 2-3 kV lower than the maximum to prevent frequent high-voltage cable breakdown.

Average operating data for each three test phases are presented in Table 3. Specific trends in the individual field voltage and current levels are not clearly recognizable, although the averaged operating levels show a slight correspondence with temperature and collection performance levels. The cause of the apparent scatter is twofold: 1) the indicated dust breakdown phenomenon causes fluctuating electrical characteristics, as evidenced in the full-scale ESP;[1] and 2) temperature and flow fluctuations experienced by the pilot ESP.

Typically, the relationship of the voltage applied and the resultant current for each precipitation field may be analyzed to gain insight into precipitator operation and performance. These corona discharge curves usually show a characteristic profile for the volt-amp relationships from each field for a given set of conditions. Compilation of corona discharge curves taken on the pilot- and full-scale ESP at Navajo reveal an exception to this approach.[1] Volt-amp relationships taken on the pilot- and full-scale system are presented in Figures 4 and 5, respectively, indicating that a broad range of operating profiles are experienced. Such variation in precipitator operation has not been explained in detail, but has been generally described as precipitator fouling or breakdown.

The operating temperature levels for each test day are shown in Figure 6. Temperature fluctuations were more pronounced in Phase I than Phases II and III. However, the time-dependent performance deterioration effect superseded any noticeable effect of temperature. Although the pilot ESP treated the flue steam over a partial temperature range (230°-330°C) compared to the full-scale ESP (270°-370°C), the operation and performance characteristics were reasonably similar. The breakdown phenomenon at Navajo does not appear to be temperature sensitive in the range of 250°-370°C.

Effect of Fly Ash Composition

Laboratory assay and resistivity determinations were performed on 32 ash samples by SRI. The individual and collective results are presented in Table 4. Ash samples were collected regularly from separate fields in the pilot ESP, with occasional samples collected directly from the plates and wires.

Sodium content was the principal compositional variant between the base ash and sodium-conditioning ash. The base ash contained an average 3.0 percent sodium, compared to 4.5 percent sodium content during conditioning. The sodium mass balance showed that 20-55 percent of the injected sodium was recoverable from the precipitator fields. Sulfur content had a corresponding increase from 0.5 percent to 1.9 percent for the base and conditioned ashes, respectively. These sulfur level results support claims that sodium ash conditioning will collect and reduce SO_x emissions.

Inspection of compositional values across the precipitator produced the following observations:

- Sodium levels varied slightly across the precipitator, showing a peak in the third and fourth fields
- Phosphorus concentrations were progressively higher from the first through the last fields
- Iron concentrations were progressively higher from the first through the last fields

The ratio of base material to sodium content is reported to be a significant indicator for hot precipitation fouling conditions.[8] The base material is composed of the oxides of calcium, potassium, sodium, iron, and magnesium. For the Navajo fly ash case of 21 percent base material, the base/sodium ratio was 4.7 and 7.0 for the conditioned and unconditioned ashes, respectively. Evidence from the pilot precipitator behavior at the reduced barometric pressures at the Navajo site (75-85 percent standard pressure) indicates the limiting base/sodium value to be 5 to 6, compared to a generalized value of 10 for standard pressure conditions. Similar reductions in precipitator stability factors are being documented for substandard pressure conditions in current research.[9]

Results of laboratory resistivity measurements are also given in Table 4. The log mean resistivity values for the base and conditioned ashes were 2×10^{10} and 5×10^{8} ohm-cm at 318°C, respectively. This 40-fold reduction in resistivity for a 1.5 percent increase in sodium content correlates with the indicated resistivity/sodium level changes from the Commanche Power Station conditioning results.[7]

COLLECTION PERFORMANCE RESULTS

The control device characteristic of practical importance is that of overall collection performance. This performance can be described and measured by the emission level which penetrates the device and passes into the atmosphere. Emission levels for each test day are grouped in chronological series in Figure 2, and are included with SCA, efficiency percentages, and averaged inlet concentrations in Table 2. Note that several emission levels have been adjusted to a common SCA value for reference.

Two methods were attempted to standardize operating SCA levels to a common value--Matts-Ohnfeldt (M-O) and Deutsch-Anderson (D-A) methods. Figures 7 and 8 show the results of the M-O and D-A methods, respectively. The transient emission levels were not grouped chronologically for averaging, but were categorized according to startup and near steady-state conditions. For Figure 7 line 'a' corresponds to startup day performance in Phase II, and lines 'b' and 'c' represent near steady-state performance with and without conditioning, respectively. For Figure 8, line 'a' corresponds to start-up and conditioning performance levels, and lines 'b' and 'c' represent Phase II and I performance levels, respectively. The data scatter under this grouping basis shows a better correspondence for the M-O than the D-A method. The more traditional D-A relationship appears to overestimate the sensitivity of SCA with collection performance from this and other data bases.

The performance model being developed by SRI was used to evaluate ESP performance.[4] A summary of this evaluation is presented in Table 5. The model predictions were computed for one ideal and two nonideal cases. The last column in Table 5 gives the ratio of actual penetration to model-predicted penetration. The model underpredicts penetration for Phase I, but overpredicts penetration for all other phases.

Fractional Data and Performance Results

Analysis of particle size data offers support and insight into collection performance. As technological advances are being made, it is becoming common knowledge that particulate control device performance is sensitive to particle size, and that size distribution data serve a principal role in performance characterization.

Results from 50 inlet impactor tests showed reasonably consistent size distribution levels for full-load boiler operation (800 MWe). A distinct distribution curve for half-load operation (350 MWe) is shown along with full-load in Figure 9. It is noteworthy that half-load boiler operation results in 37 percent higher overall loading because of a higher concentration of large particles (above 5 microns). Figure 9 shows a greater inlet concentration in the ESP-vulnerable size range of 0.3 to 1.5 microns at full-load than at half load. The differential concentration in this size range could explain the superior performance of Phase III B (half-load) to Phase III A (full load) despite the lower temperature of Phase III B.

Comparison of fractional penetrations for Phase II and III A are shown in Figure 10. Sodium conditioning enhanced performance across the particle size range, but enhancement decreased with smaller particle sizes. Figure 10 also includes comparison of the SRI model predictions for the respective conditions of Phases II and III A.

RECOMMENDATIONS FOR FUTURE HOT-SIDE EVALUATIONS

- Extend temperature range of evaluation up tc 380°C
- Conduct evaluation with in-situ resistivity probe to determine real time and possible timedependent resistivity and breakdown levels
- Evaluate another hot-side case at standard pressure levels
- Evaluate sensitivity of hot-side performance on fly ash composition

REFERENCES

1. Marchant, G.H., Jr., and L.E. Sparks. A Performance of a Hot-Side Electrostatic Precipitator. Symposium on the Transfer and Utilization of Particulate Control Technology: Volume I, Denver, Colorado, 1978. EPA-600/7-79-044a. pp. 39-56.

2. Nichols, G.B. and D.L. Harmon. Preliminary Design and Initial Testing of a Mobile Electrostatic Precipitator. EPA-600/7-78-096, U.S. Environmental Protection Agency, Research Triangle Park, NC, June 1978.

3. Lawless, P.A. Analysis of Cascade Impactor Data for Calculating Particle Penetration. EPA-600/7-78-189, U.S. Environmental Protection Agency, Washington, DC, September 1978. 39 p.

4. McDonald, J.R. and L.E. Sparks. A Mathematical Model of Electrostatic Precipitation (Revision I): Volumes I and II, EPA-600/7-78-111a. U.S. Environmental Protection Agency, Research Triangle Park, NC June 1978.

5. Maartman, S. and A.B.S. Filaktfäbriken. Experience with Cold-Side Precipitators on Low Sulfur Coals. Symposium (Ref. 1). EPA-600/7-79-044a. p. 26.

6. Electrostatic Precipitation Technology: A Different Viewpoint. Journal of Air Pollution Control Association. January 1978.

7. Lederman, P.B., P.B. Bibbo and J. Bush. Chemical Conditioning of Fly Ash for Hot-Side Precipitation. Symposium on the Transfer and Utilization of Particulate Control Technology: Volume I, Denver, Colorado, 1978. EPA-600/7-79-044a. pp. 79-98.

8. Atkins, S. and D. V. Bubenick. Keeping Fly Ash Out of the Stack. Environmental Science and Technology, 12:6, 1978.

9. Bush, J.R., et al. Development of a High-Temperature/High-Pressure Electrostatic Precipitator. EPA-600/7-77-132, U.S. Environmental Protection Agency, Research Triangle Park, NC, November 1977. 69 p.

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TABLE 1 COMPARISON OF PILOT- AND FULL-SCALE ESP DESIGN AND OPERATING SPECIFICATIONS

DESIGN	FULL SCALE[3]	PILOT ESP
Discharge wire diameter, cm	0.27	0.25
Wire-wire spacing, cm	22.9	18
Wire-plate spacing, cm	11.4	12.7
Collection area/T-R set, m^2	2340	9
Aspect ratio	0.2	0.67
Gas Velocity, m/sec	0.8-1.6	0.7-1.3
No. of fields in series	6	5
OPERATION		
Secondary voltage, kV	22	29.7
Secondary current density, nA/cm^2	40	14
Specific collection area, $m^2/m^3/sec$	65	60-100
Inlet gas temperature range, °C	300-370	230-330
Inlet particulate concentration, g/dsm^3	5.4	9.0
Measured efficiency range, %	98.5	95-99.8

TABLE 2 SUMMARY OF ESP TEST DATA

TEST NUMBER	TEST DATE 1978	SEQUENTIAL OPERATING DAY	SCA $m^2/m^3/sec$	SERIES AVERAGE INLET LOADING gm/DNCM	OUTLET EMISSION LEVEL gm/DNCM	EFFICIENCY PERCENT	D-A EFFICIENCY FOR SCA=88.6 $m^2/m^3/sec$	D-A OUTLET LOADING gm/DNCM	M-O EFFICIENCY FOR SCA=88.6 $m^2/m^3/sec$	M-O OUTLET LOADING gm/DNCM
1	6/7	1	102.6	9.31 PHASE I	0.508	99.45	98.88	0.104	99.2	0.074
2	6/8	2	104.8		0.059	99.37	98.61	0.129	99.1	0.084
3	6/9	3	102.6		0.145	98.44	97.25	0.256	97.9	0.195
4	6/12	0	102.6		0.0476	99.49	98.94	0.098	99.26	0.069
5	6/13	1	104.8		0.054	99.42	98.71	0.120	99.12	0.082
6	6/14	2	63.0		0.764	91.8	97.63	0.277	96.04	0.368
7	6/15	3	104.8		0.823	91.2	87.1	1.20	89.22	1.003
8	6/20	0	83.9		0.0412	99.56	99.67	0.031	99.62	0.0354
9	6/21	1	104.8		0.019	99.8	99.47	0.049	99.67	0.031
10	6/22	2	104.0		0.332	99.44	94.2	0.542	95.40	0.428
11	6/23	3	0		3.751	59.7	-	-	-	-
12	7/11	1	118.1	9.31 PHASE II	0.084	99.1	97.08	0.272	98.3	0.0692
13	7/12	2	99.4		0.154	98.3	97.35	0.247	97.86	0.087
14	7/13	3	88.9		0.236	97.47	97.44	0.238	97.47	0.103
15	7/14	4	65.9		0.357	96.17	98.77	0.114	97.73	0.0924
16	7/18	1	70.2		0.062	99.33	99.82	0.017	99.63	0.015
17	7/19	2	65.5		0.111	98.82	99.75	0.023	99.43	0.023
18	7/20	3	82.4		0.087	99.07	99.34	0.061	99.21	0.032
19	7/25	0	82.4		0.077	99.17	99.42	0.054	99.3	0.0285
20	7/26	1	85.7		0.058	99.38	99.47	0.049	99.43	0.0232
21	7/27	2	83.9		0.087	99.06	99.27	0.068	99.17	0.0338
22	7/28	3	98.3		0.136	98.52	97.74	0.210	98.16	0.0749
23	7/31	0	104.8		-	-	-	-	-	-
24	8/1	1	98.3		0.063	99.32	98.88	0.104	99.12	0.0358
25	8/2	2	82.1		0.135	98.55	98.96	0.097	98.77	0.050
26	8/3	3	0		3.169	66.0	-	-	-	-
27	8/8	0	81.7	8.851 PHASE IIIA	0.148	98.41	98.87	0.105	98.65	0.126
28	8/9	1	88.9		0 094	99.00	99.00	0.094	99.0	0.093
29	8/10	2	98.6		0.055	99.41	99.00	0.094	99.22	0.072
30	8/11	3	98.6		0.077	99.17	98.64	0.126	98.93	0.099
31	8/14	0	103.7		0.026	99.71	99.31	0.063	99.55	0.042
32	8/22	0	58.0	12.58 PHASE IIIB	0.116	98.75	99.88	0.015	99.56	0.041
33	8/23	1	58.0		0.171	98.17	99.79	0.027	99.30	0.065
34	8/24	2	58.0		0.167	98.20	99.80	0.026	99.32	0.063
35	8/25	3	64.8		0.140	98.49	99.68	0.041	99.26	0.069

TABLE 3 AVERAGE OPERATING LEVELS FOR PILOT ESP

FIELD NUMBER	PHASE I		PHASE II		PHASE IIIA		PHASE IIIB	
	V	I	V	I	V	I	V	I
1	37.4	4.3	30.5	3.63	30.8	4.64	36.0	6.33
2	26.6	1.13	24.7	1.29	24.8	1.68	26.5	0.7
3	30.8	11.6	29.3	4.83	28.8	5.34	32.0	8.01
4	26.0	29.9	26.0	13.1	25.4	15.3	27.8	11.8
5	27.8	14.8	25.9	11.5	24.8	8.63	27.5	8.6
AVERAGE	29.7	12.3	27.3	6.9	26.9	7.1	30.0	7.1

V = Kilovolts, kV

I = Current Density, nA/cm2

TABLE 4 RESULTS OF FLY ASH ANALYSIS

PHASE	TEST NUMBER	DATE	FIELD NUMBER	Na_2O PERCENT	SO_3 PERCENT	K_2O PERCENT	P_2O_5 PERCENT	Fe_2O_3 PERCENT	BASE PERCENT	BASE/ Na_2O	RESISTIVITY AT 5KV/CM 318°C, 9% H_2O Ohm · cm
I	1	6/7	1	2.2							
	3	6/9	1	2.6							
	3	6/9	3	3.2							
	3	6/9	4	3.4							
	5	6/13	1	2.7	0.57	1.1	0.13	4.7	15.4	5.7	
	5	6/13	3	4.5		1.4	0.34	5.7	25.7	5.7	
	5	6/13	5	3.8		1.3	0.46	7.4	23.2	6.1	
	7	6/15	1	3.1		1.4	0.18	5.4	22.0	7.1	
	7	6/15	4	3.5		1.4	0.26	6.5	21.7	6.2	
	7	6/15	5	3.4		1.4	0.33	6.6	21.4	6.3	2.0×10^{10}
				AVG: 3.24							
II	21	7/27	1	2.4							
	21	7/27	3	3.0							
	21	7/27	5	3.0							
	22	7/28	1	2.6	0.45	1.7	0.18	6.1	17.2	6.6	
	22	7/28	3	3.2		1.9	0.21	6.5	19.2	6.0	
				AVG: 2.84							
IIIA	27	8/8	1	3.0		1.3	0.14	6.3	20.1	6.7	
	27	8/8	3	3.6		1.3	0.26	7.3	22.7	6.3	
	27	8/8	5	3.6		1.1	0.27	7.2	22.7	6.3	
	29	8/10	3	-							6.2×10^7
	30	8/11	1	7.1		1.3	0.22	5.2	20.6	2.9	1.4×10^8
	30	8/11	5	5.0		1.3	0.56	7.5	25.0	5.0	
	31	8/14	W-1	4.3							
	31	8/14	W-2	5.4							
				AVG: 4.6							
IIIB	32	8/22	1	5.6							1.4×10^8
	32	8/22	5	4.7							
	32	8/22	W-3	4.7		1.5	0.37	5.0	18.3	3.9	6.5×10^8
	32	8/22	W-5	4.7	1.3	1.5	0.41	7.0	18.8	4.0	
	32	8/22	P-3	3.7	2.0	1.4	0.47	6.8	22.2	6.0	
	32	8/22	P-5	4.0	2.3	1.4	0.49	6.9	22.4	5.6	
	33	8/23	3	-							8.3×10^8
	34	8/24	1	3.4							3.5×10^9
	35	8/24	5	3.3							
	35	8/25	1	4.2							6.0×10^8
	35	8/25	5	4.6							
				AVG: 4.3							

TABLE 5 COMPARISON OF DATA WITH MODEL PREDICTED PERFORMANCE

PHASE	AVERAGE TEMPERATURE, °C	SODIUM INJECTED PERCENT	APPROXIMATE STEADY-STATE PENETRATION PERCENT	MODEL PREDICTED PENETRATION PERCENT	ACTUAL PENETRATION/ PREDICTED PENETRATION
I	260	NIL	4.66	*a. 1.83	2.55
				*b. 2.60	1.79
				*c. 3.50	1.33
II	294	NIL	1.82	a. 3.96	0.46
				b. 6.09	0.30
				c. 8.1	0.22
IIIA	294	8.16	0.74	a. 3.38	0.22
				b. 5.29	0.14
				c. 7.15	0.10
IIIB	246	2.33	1.6	a. 6.98	0.23
				b. 10.04	0.16
				c. 12.8	0.125

*a. ASNUCK = 0.0 AZIGGY = 0.00
b. ASNUCK = 0.1 AZIGGY = 0.25
c. ASNUCK = 0.1 AZIGGY = 0.50

ASNUCK = cell bypass fraction
AZIGGY = normalized standard deviation of inlet velocity

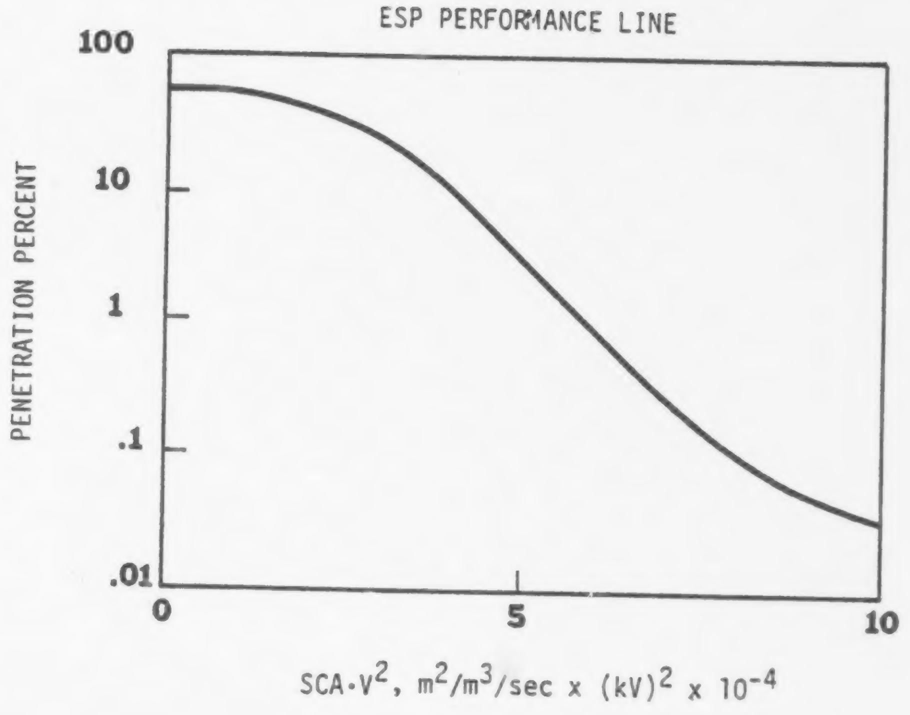

Figure 1 Actual ESP performance relationship.

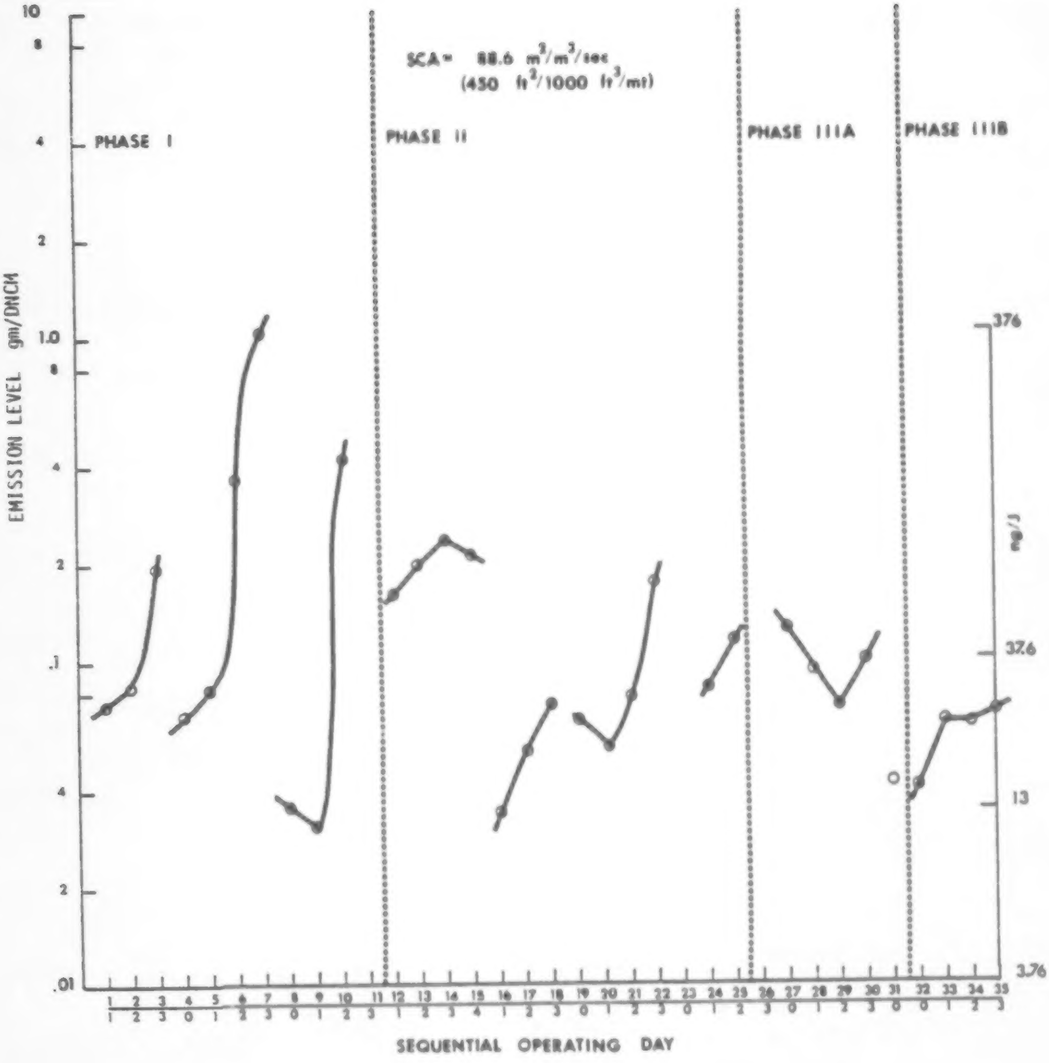

Figure 2 Matts-Ohnfeldt common SCA adjusted emission level versus sequential operating day.

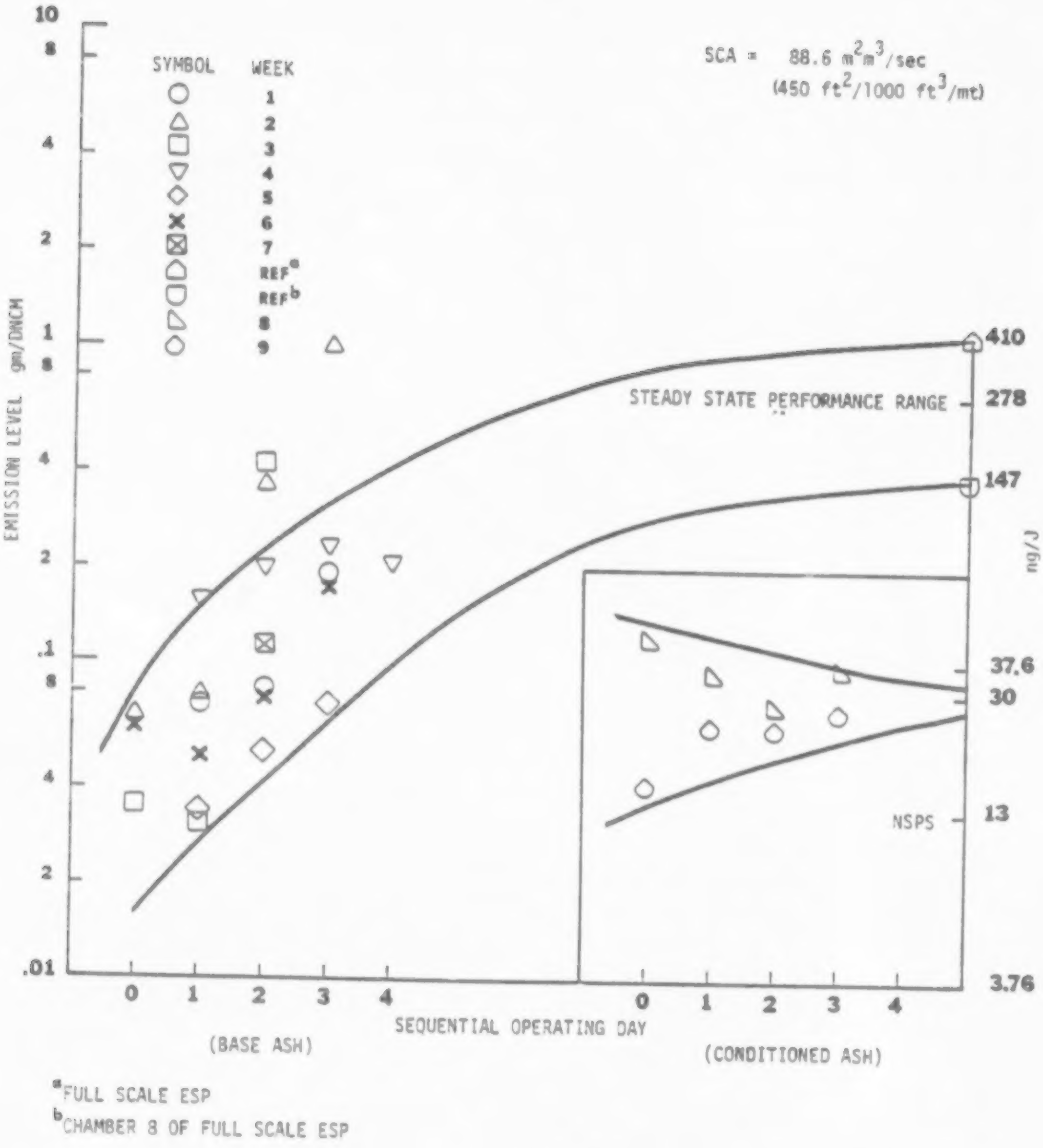

Figure 3 Matts-Ohnfeldt common SCA adjusted emission level versus sequential operating day.

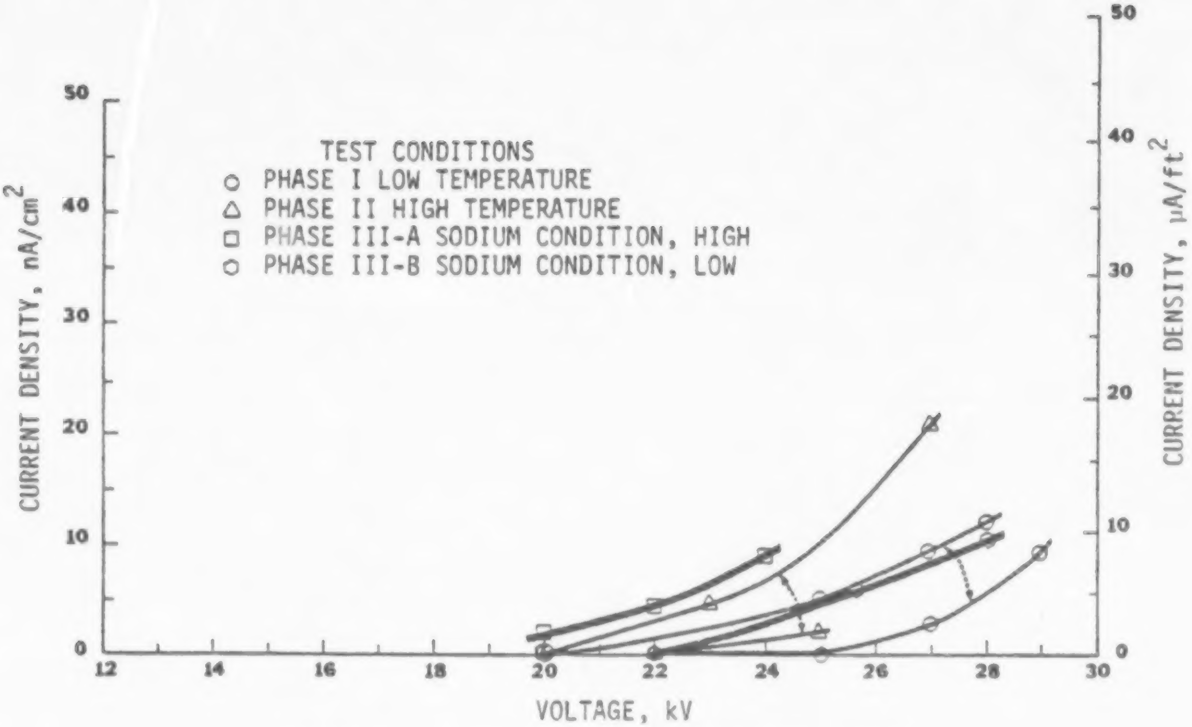

Figure 4 Pilot ESP Corona Discharge Curves.

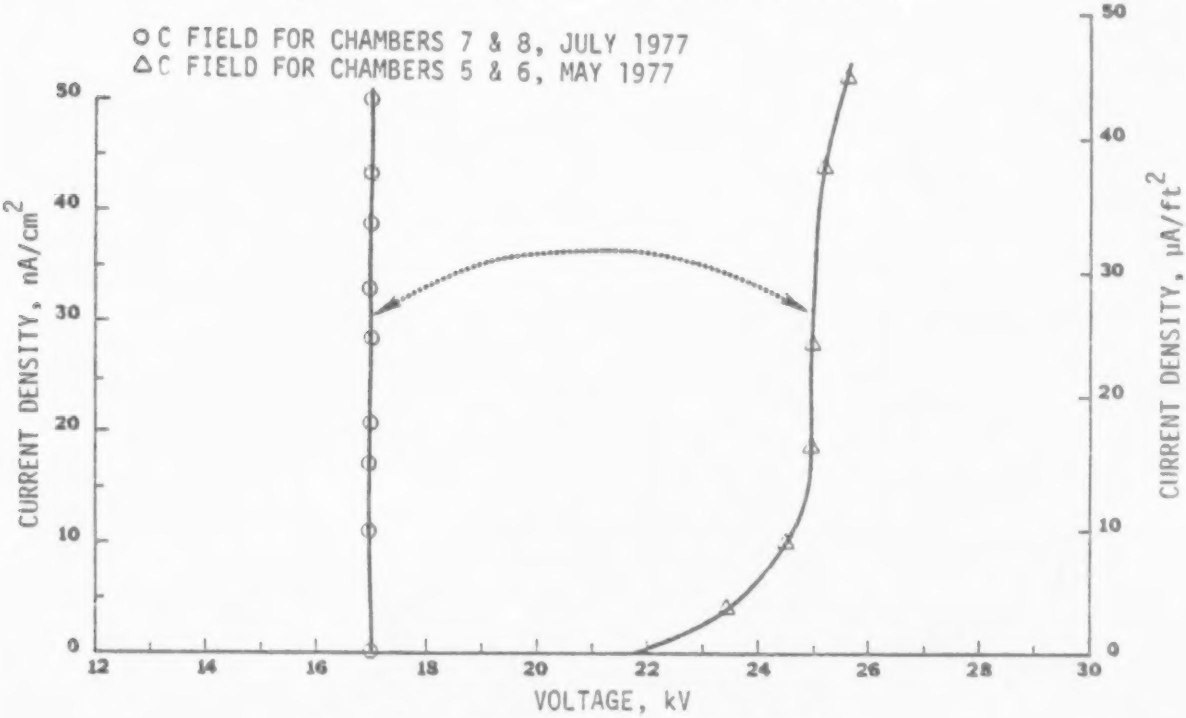

Figure 5 Full scale ESP Corona Curves.

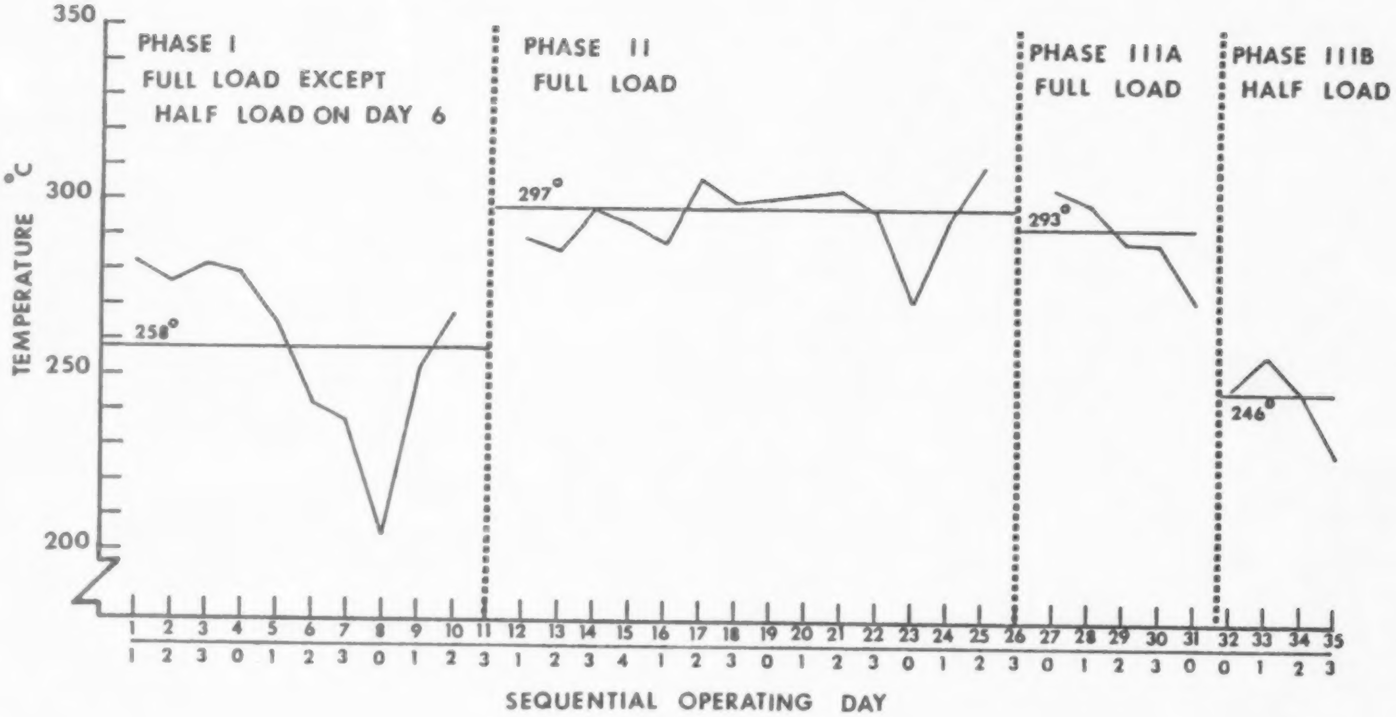

Figure 6 Pilot ESP test temperature versus sequential operating day.

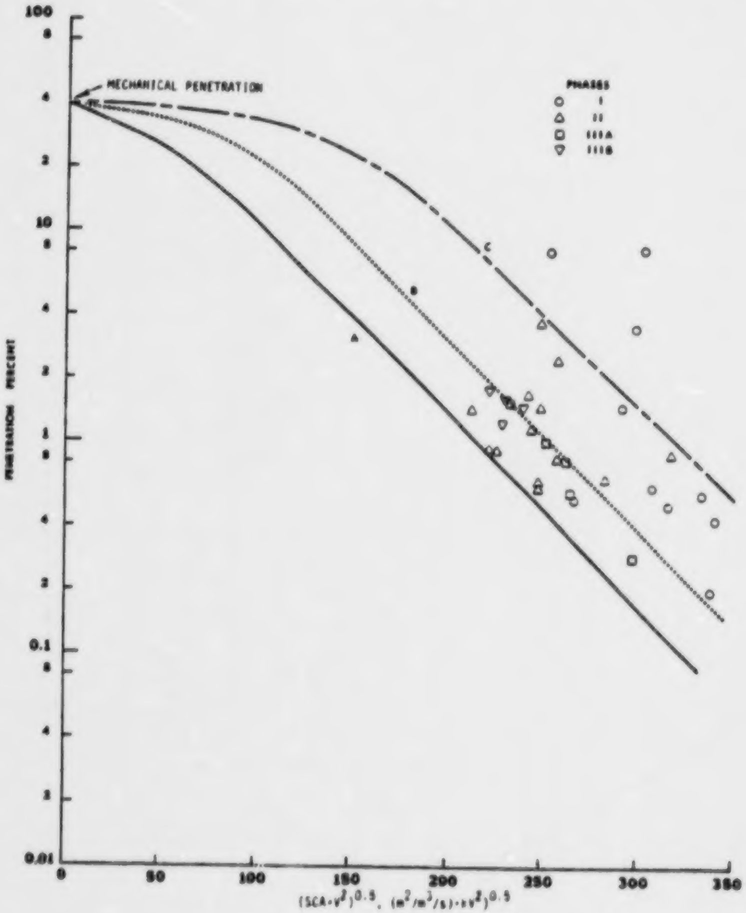

Figure 7 ESP performance line based on extended Matts-Ohnfeldt equation.

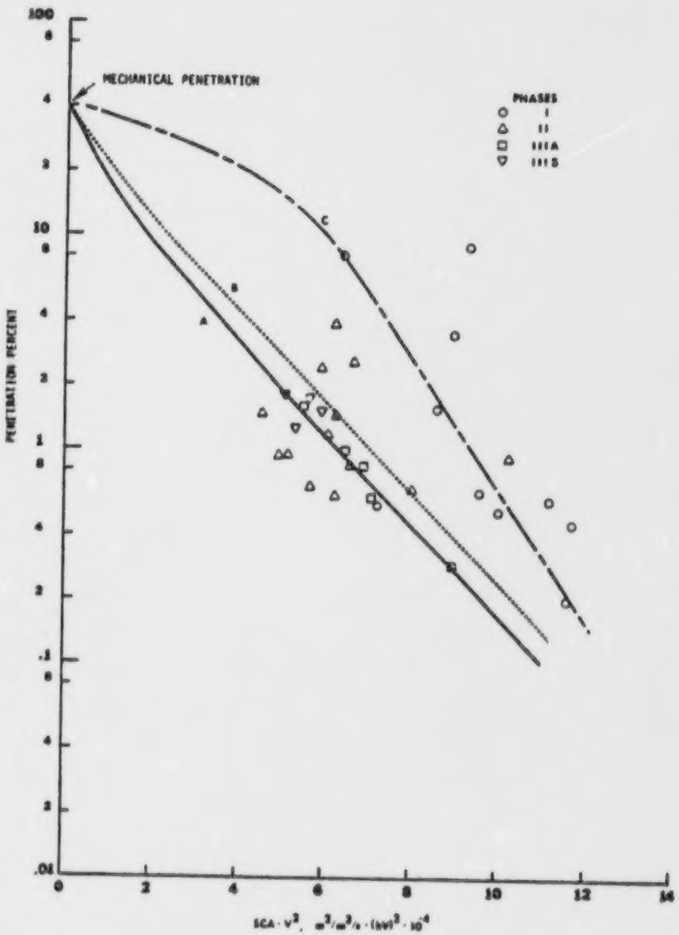

Figure 8 ESP performance lines based on extended Deutsch-Anderson equation.

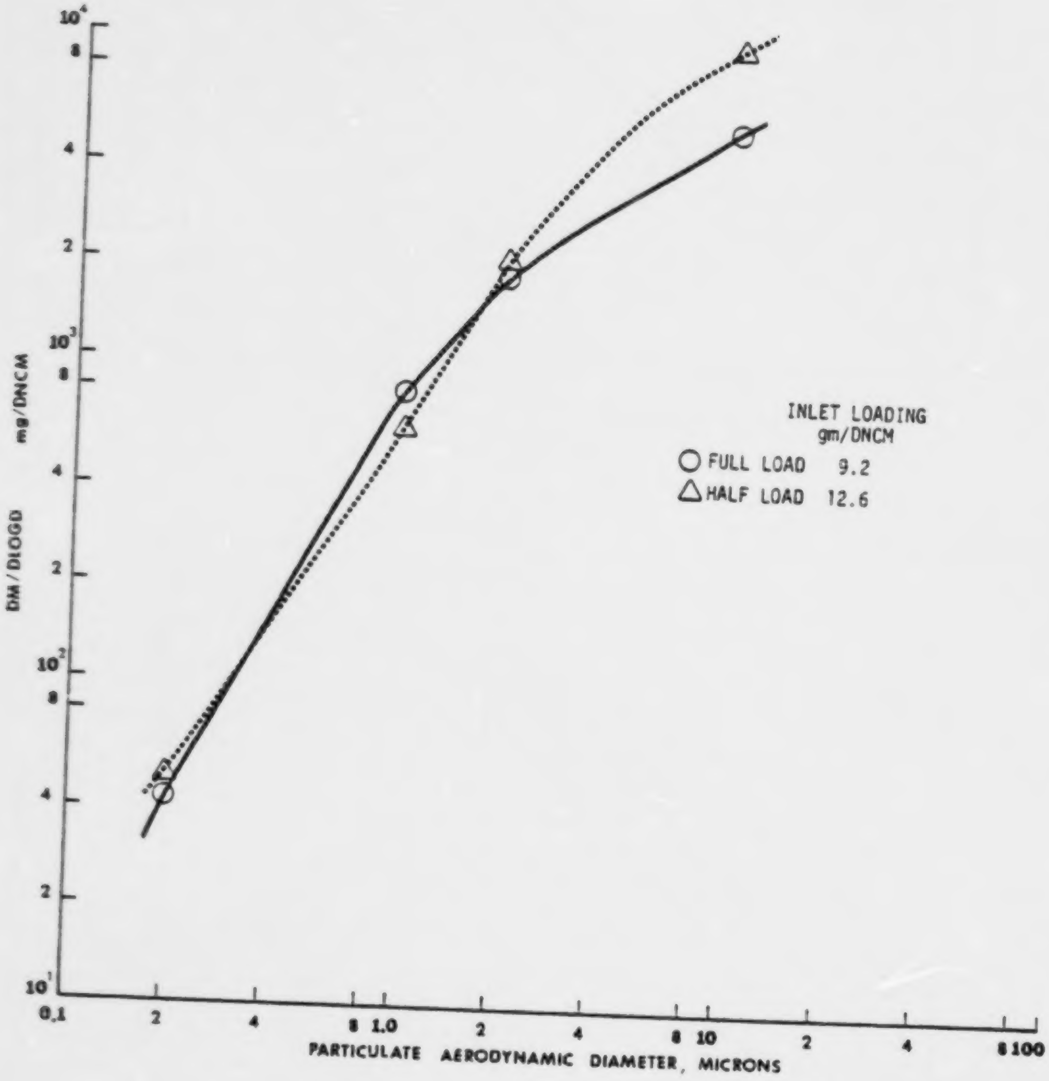

Figure 9 ESP average influent characteristics with 90% confidence limits for full and half load boiler operations.

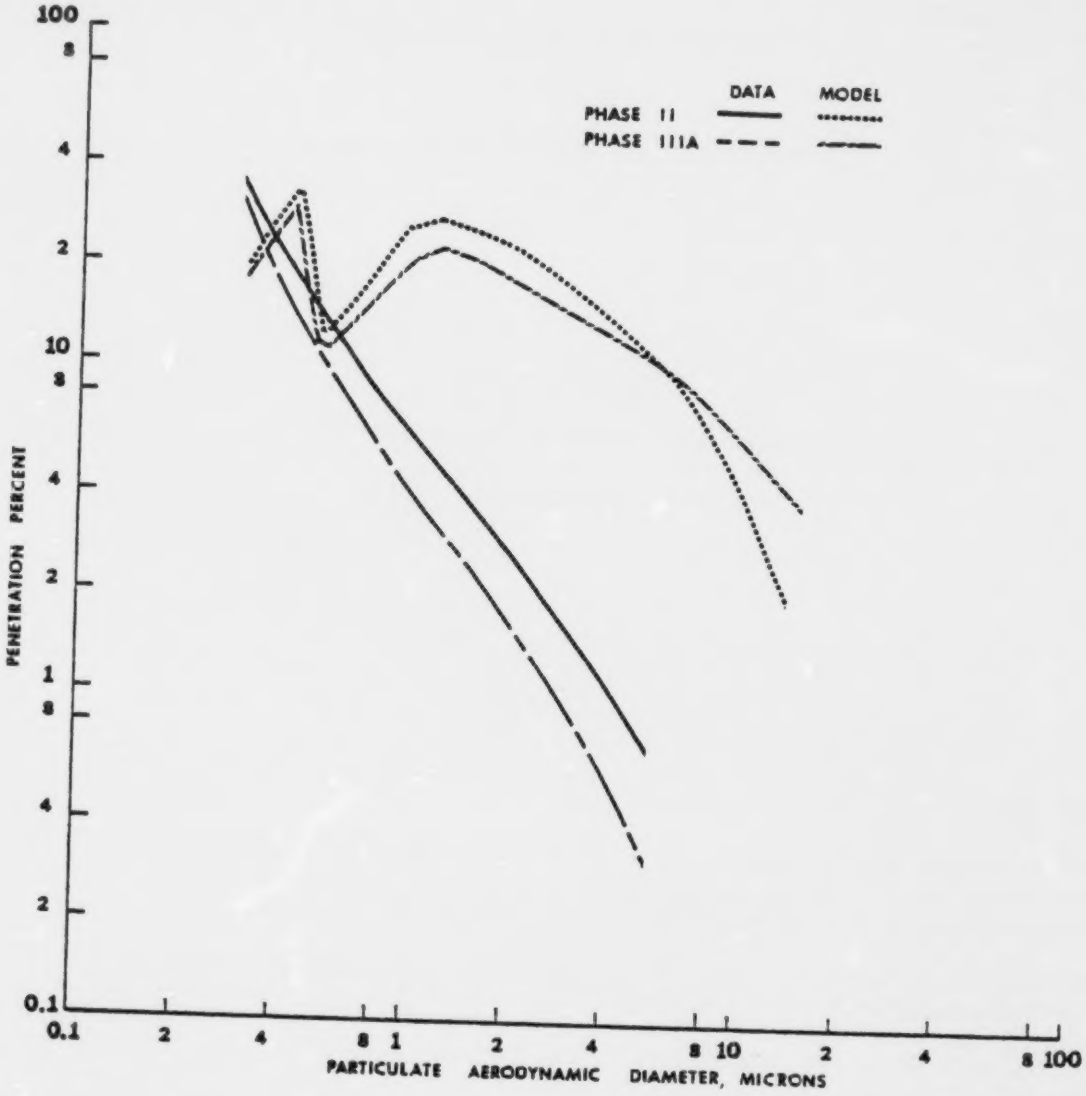

Figure 10 Comparison of fractional penetrations with predictions.

PRECIPITATOR UPGRADING AND FUEL CONTROL PROGRAM FOR PARTICULATE COMPLIANCE AT PENNSYLVANIA POWER AND LIGHT COMPANY

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ABSTRACT

Two cold side electrostatic precipitators handling low sulfur Eastern bituminous coal flyash were upgraded from 94% to 99.4% efficiency in order to meet a particulate compliance limit of 0.1 lb/MMBTU.

The comprehensive upgrading was the result of a two year research and testing program during which various aspects of flue gas conditioning, electrical energization, rapping, coal quality control and gas distribution were independently tested on three similar precipitators. The ensuing upgrading program included the installation of hardware designed for maximum performance and reliability as well as flue gas conditioning and a fuel ash control program.

A cost and reliability analysis of the upgrading program as compared with the installation of an additional series precipitator is included.

INTRODUCTION

In 1974, Pennsylvania Power and Light Company (PP&L) was faced with the problem of having several generating units which did not comply with the particulate emissions regulations of the Pennsylvania Department of Environmental Resources. This paper deals with the approach taken to analyze and solve the emissions problems on three similar units.

The three units are Montour Units 1 and 2, located in Washingtonville, Pennsylvania, and Brunner Island Unit 3, York-Haven, Pennsylvania. Each unit is nominally rated at 750 MW and is equipped with a Combustion Engineering tangentially fired boiler burning Eastern bituminous coal pulverized to 70% through 200 mesh consistency. Each boiler is equipped with a Western Precipitation electrostatic precipitator (ESP) in a chevron arrangement with a total specific collecting area (SCA) of $40m^2/(m^3/sec)$ ($204\ ft^2/1000\ cfm$) at design flow of 1062 m^3/sec (2,250,000 acfm) at 149°C (300°F). Under actual boiler operating conditions, an SCA of only 35 $m^2/(m^3/sec)$ ($180\ ft^2/1000\ cfm$) is achieved.

Although these ESP's had a guaranteed design efficiency of 99.5%, this level of performance was never achieved under actual operating conditions. In fact, due to degrading fuel quality, changes in boiler operation to prevent slagging and the small size of the ESP's, efficiencies of only about 94% were achieved with low sulfur coal (1.0%S).

In late 1974, a project team was established to study the ESP problems on these units as well as one smaller unit (Brunner Island 1). This Air Quality Project (AQP) team consisted of seven full time engineers. The basic objective of the AQP was to assure that compliance was achieved, but also to minimize the compliance cost by placing primary emphasis on upgrading the existing collectors rather than installing new ones.

From March 1975 until March 1977, a variety of parameters which affect ESP performance were investigated by the AQP team. The areas of investigation included:

- Fuel Quality
- Flue Gas Conditioning
- ESP Sectionalization
- Rappers
- High Voltage Controllers
- Flue Gas Distribution
- Reliability Items

Each of the above areas was independently investigated by a member of the AQP. When the investigations indicated that a change in a particular area could improve ESP performance or reliability, the change was implemented on one single unit on a trial basis. To fully evaluate the change, ESP efficiency tests were run after each trial change and the results were compared with baseline data. A total of 47 full efficiency tests were run on the four units during the two year investigation. In addition, continuous opacity monitor data was used for comparative purposes whenever it was impractical or inconvenient to run an efficiency test.

As a result of the AQP investigation, the Montour ESP's were upgraded to achieve particulate compliance instead of building additional collectors. Although Brunner Island Unit 3 is similar to Montour Units 1 and 2, this unit could not achieve compliance through upgrading due to dissimilar boiler operation and an inability to control long range coal quality at the Brunner Island station. Due to these differences a series ESP was installed on Brunner Island Unit 3.

With the exception of a cost and performance comparison between the upgrading modes selected for Brunner Island 3 and Montour, the remainder of this paper deals with the Montour upgrading investigation and implementation phases.

RESULTS OF THE INVESTIGATION PHASE

FUEL CONTROL

Bituminous coal burned on the PP&L system is obtained both from company affiliated mines and from numerous open market sources. The quality of the coal is highly variable with sulfur content ranging from 0.8% to 2.5% and ash content ranging from 11% to 25%. The fuels investigation that was performed by the AQP team sought to quantify the effect of sulfur content and ash content on ESP efficiency and to determine if fuel quality could realistically be controlled to improve ESP performance.

A high sulfur (2.4% S) low ash (12% Ash) coal supplied by Benjamin Coal Company was used for benchmark data since it was considered to be one of the best collecting coals (as measured by the achieved ESP efficiency) burned on the system. The ESP efficiencies measured while burning Benjamin coal were compared with efficiencies of lower sulfur coals of various ash content. Several important conclusions which were applicable to all four of the tested units were drawn from these tests.

- A coal sulfur content of 2.2% or greater was required to obtain optimum ESP efficiency.

- Given a constant sulfur content, ESP efficiency did not change as the ash content was varied in the 11% to 25% range.

- As the ash content of the coal increased, the percentage of ash that found its way into the ESP's in the form of fly ash decreased. Prior to this investigation, it was assumed that 80% of the ash in the coal "carried over" into the ESP's in the form of flyash. As can be seen in Figure 1, the percentage of flyash carryover was found to be inversely proportional to the ash content.

- Due to the lower percentage of fly ash carryover in the higher ash coals, the ESP efficiency which is required to meet the 0.1 lb/MMBTU compliance limit does not have a linear relationship with the ash content of the fuel (Figure 2). It is apparent from Figure 2 that an ESP efficiency of 99.3% would be sufficient to meet the particulate compliance limit of 0.1 lb/MMBTU with any of the tested coals.

The conclusions drawn from the Fuels Investigation provided the basis for the decision to upgrade the existing Montour ESP's rather than adding new collectors. While testing with the Benjamin coal at Montour, an ESP efficiency of 99.4% was achieved, thus indicating that compliance could in fact be attained under controlled conditions.

Unfortunately, under low (1.0%) sulfur coal conditions, ESP efficiency would degrade to below 94%. Due to the fact that the major supplier of coal for the Montour station is Greenwich Collieries, a PP&L affiliated mine which produces a coal with a low average sulfur content (1.2% S) it was not feasible to establish a fuel procurement plan which would eliminate low sulfur coal.

FLUE GAS CONDITIONING

Due to the observed detrimental effect of low sulfur coal on ESP performance, the use of SO_3 flue gas conditioning as a resistivity modifier was investigated by the AQP.

After a careful evaluation of industry experience with SO_3 conditioning, a trial SO_3 injection system was installed on Brunner Island Unit 1 (BI-1). BI-1 was selected for the trial because it was the smallest unit under investigation and therefore the installation costs of the system could be kept to a minimum.

To evaluate the effect of SO_3 conditioning, our benchmark coal (Benjamin) was tested without SO_3 injection to establish a "maximum" ESP efficiency for BI-1. A second coal with low sulfur content (1.0% S) from Greenwich Collieries (the major coal supplier for Montour) was then tested both with and without SO_3 conditioning. The tests run without the SO_3 conditioning indicated that the Greenwich coal was one of the poorest collecting coals normally burned. However, with the addition of 25 ppm of SO_3, the ESP efficiency with Greenwich coal improved to a level slightly better than that measured with Benjamin. The tests results are summarized in Figure 3.

Supplemental testing using opacity monitors and flyash resistivity probes as performance indicators revealed that SO_3 conditioning was capable of offsetting the effects of burning low sulfur coal to the degree of maintaining optimum ESP efficiency with virtually any coal normally burned at either Montour or Brunner Island.

Since the use of SO_3 as a flue gas conditioning agent had demonstrated repeatable and predictable results, the AQP concluded that SO_3 conditioning was a viable alternative for improving ESP performance under conditions of high resistivity flyash resulting from burning low sulfur coal.

It should also be noted that another flue gas conditioning trial was conducted at Montour using proprietary chemicals. Although some improvements in stack opacity had been achieved, no significant improvements in ESP efficiency were measured during the trial period.

ESP ELECTRICAL ENERGIZATION

Electrical energization was investigated in two primary areas; a) Automatic high voltage control systems and b) Transformer - Rectifier (TR) set capacity.

A. Automatic High Voltage Controls

At the time that the AQP investigation began, almost all of PP&L's precipitators were equipped with high voltage controllers which used saturable core reactors (SCR) and outdated control logic. The investigation therefore focused on modern thyristor controllers with compatible high speed control logic. A series of full scale trials using thyristor controllers was subsequently conducted.

The ability of a modern control to greatly improve ESP efficiency was not demonstrated during this study. Power levels (V and I) were increased in some units but the ESP efficiencies did not noticeably change from the values measured before installation of the new controls. Operational experience indicated, however, that the frequency of wire failures was greatly reduced after the new controllers were installed. Heavy sparking and wire burning were almost completely eliminated. It was concluded that the new controls would improve reliability while maintaining voltage and current levels.

B. TR Set Capacity

During the SO_3 conditioning trial at Brunner Island, it was noted that most TR sets operated at the current limit when SO_3 conditioning was utilized. Further investigation and trial operation revealed that for optimum ESP efficiency with SO_3 conditioning, the TR sets should be sized large enough to provide a current density of at least 54 na/cm^2 (50 $ma/1000\ ft^2$), particularly in the outlet sections.

GAS DISTRIBUTION

Due to the unusual chevron shaped inlet duct on the Montour ESP's (Figure 4), an investigation into the possibility of poor gas distribution within the ESP's was undertaken.

Motivated by what later proved to be an erroneous air load velocity test performed by a subcontractor, the AQP contracted to have an ESP model constructed and a model study performed.

The results of both the model study and subsequent field tests revealed that the ESP's were operating with an RMS velocity deviation of about 12.5% which is well within the standards of the Industrial Gas Cleaning Institute (I.G.C.I.).

Further model studies were conducted to determine whether the velocity distribution could be further improved. An additional 50% open perforated plate was subsequently installed on one-half of one ESP for evaluation. Since ESP efficiency testing did not indicate that the additional perforated plate had resulted in a performance improvement, no additional modifications were made to the remaining chevron ESP's.

RAPPERS

The Montour ESP's were initially equipped with vibrating rappers and electromechanical (cam type) rapper controls. The need for better rapping was evident from the heavy plate deposits which were routinely observed during internal ESP inspections.

As part of the rapper evaluation study, 96 electric impact collecting plate rappers were installed on one-half of the Montour 2 ESP, replacing the existing vibrating rappers. In addition, an electronic matrix type rapper controller with the ability to quickly change rapper timing, intensity and programming, was installed to control the new rappers.

Tests results indicated that the impact rappers did a significantly better job of cleaning the collecting plates than did the vibrating rappers, and that the clean plates resulted in an improvement in ESP performance. The testing also indicated the need for a programmable rapper control which was capable of minimizing rapping intensity and frequency on the outlet sections in order to minimize rapping reentrainment.

Additionally, it was concluded that the existing configuration of one rapper for every seven plates did not provide sufficient cleaning of the plates which were farthest from the rapper. An improved arrangement of one rapper for every three plates was suggested.

THE MONTOUR UPGRADING PROJECT

CAPITAL IMPROVEMENTS

The results obtained from the individual investigations which were performed by the AQP team were utilized to formulate a comprehensive upgrading program for Montour. A key aspect of the upgrading was to achieve an ESP efficiency of 99.4% (as previously seen while burning Benjamin coal) and to maintain this level of performance, as much as possible, for the wide variety of coals and operating conditions encountered at Montour. To accomplish this objective, the following improvements were incorporated:

- An SO_3 flue gas conditioning system was installed on each unit to offset the effects of low sulfur coals which account for two-thirds of the station's fuel supply. The sulfur burner type system was equipped with sufficient redundant equipment (including spare boilers, air heaters and sulfur pumps) to ensure 95+% reliability of the system. The SO_3 system feed rate is varied according to the unit load and the sulfur content of the coal being burned in order to maintain a total SO_3 concentration of 19 ppm at the inlet to the ESP (including that portion of SO_3 produced by the coal being burned). This corresponds to a fly ash resistivity of about 5×10^{10} ohm-cm.

- The existing rappers and rapper controls were replaced with electric impact rappers and matrix type rapper controls with considerable programming flexibility. The number of rappers used for plate rapping was approximately doubled in number so that each impact rapper would clean either three or four plates. Impact rappers were also installed on the high voltage discharge system.

- All automatic high voltage electrode controls were replaced with thyristor type controls. In addition, secondary (d-c) metering (voltage, current and spark rate) was installed for each TR set in order to provide better information for operating personnel.

- The number of TR sets utilized on each half of the ESP chevron was increased from 8 to 14. The original ESP design utilized one TR set to power two sections. This arrangement was changed on all but the inlet sections to allow one TR set per section, thus increasing the available current density on the outlet sections to 97na/cm^2 (90ma/1000 ft^2). The original and final arrangements are shown in Figure 4.

- Each ESP was refitted with new discharge wires as part of the upgrading. Additionally, each unit originally had a double wire per weight high voltage framework design which was modified to a single wire per weight framework.

- Each hopper was equipped with nuclear type hopper level detectors and electric hopper heaters in order to minimize the possiblity of hopper overfill. This improvement was made because the AQP had identified hopper overfilling as a leading cause of ESP section outages.

- In order to implement the various phases of the Montour upgrading project,one full-time engineer was added to the plant staff. In addition, the position of ash equipment operator (one per shift) was established at the plant. The ash equipment operator is responsible for ESP operation, ash removal equipment operation and SO_3 system operation.

FUEL CONTROL PLAN

A unique aspect of the Montour upgrading program is the inclusion of a fuel ash control plan.

As previously outlined and illustrated in Figure 2, an ESP efficiency of 99.3% is sufficient to handle coals of ash contents of up to 25%. In order to incorporate additional operating margin and reliability into the upgrading plan, the ash content of coals shipped to Montour has been restricted to less than 17% (d.b.). As can be seen from Figure 2, an ESP efficiency of about 99.1% would be sufficient for coals of this quality.

Approximately 60% of the coal burned at Montour is supplied by Greenwich Collieries, which ships 100% of its produced coal to Montour. The mine is equipped with a modern coal cleaning plant capable of producing coal as low as 8% ash. As a compromise between mine economics and Montour ESP reliability, the average ash content shipped from Greenwich is about 14% with virtually all of the coal being less than 17% ash.

Most of the remainder of Montour's coal supply is purchased on the open market. The vendors which ship to Montour are presently restricted to a 14% ash content and are selected by the PP&L Fuels Department based on their history of quality control. Vendors which ship a single trainload (13,000 tons) of coal to Montour which is in excess of 17% ash are subjected to a field investigation by the Fuels Department. If the shipment is in excess of 19% ash, all future shipments from that vendor are suspended until quality assurance is reestablished.

An "early warning" system has been established which allows the Montour plant to know the ash content of all coal shipped to the plant before it arrives. All of the coal burned at Montour is shipped to the plant in PP&L owned fleet trains. An independent coal analysis firm has been hired to sample coal from each car in the fleet train at the time that it is loaded at the mine. The analysis firm then performs a "quick ash analysis" which takes about three hours and has proven to be fairly accurate. The results of the quick ash analysis are teletyped to Montour in less than 12 hours from the time the sample is taken. (Train transit time is 12 - 24 hours.)

In the event that a high ash shipment of coal arrives at Montour, the early warning system allows the plant to take appropriate action.

The plant's coal yard is equipped with a stacker reclaimer with capacity to hold 5 trainloads of coal. Sufficient area is reserved on the stacker reclaimer at all times for the storage of at least one trainload of high ash coal (greater than 17% ash). If the early warning system reveals that a trainload of high ash coal will arrive at the station, the coal is unloaded into the reserved storage area. From this area, the coal is reclaimed on a controlled basis and mixed with coal of lower ash content. Since the Montour plant has three raw coal silos per unit, the mixing is usually accomplished by loading high ash coal in one silo and low ash coal in the other two silos. In this manner, a 13,000 ton trainload of high ash coal can be safely disposed of in about one week. A schematic layout of the Montour high ash coal handling system is shown in Figure 5.

RELIABILITY ANALYSIS

Before the decision was made to upgrade the Montour ESP's, a comprehensive reliability analysis of all components that would be a part of the upgrading was undertaken. Essentially, the objective was to determine the percentage of time that the Montour units could be expected to remain in compliance, given the known fallibility of some aspects of the compliance plan. This was an important consideration in light of the fact that the units would probably have to drop load (at substantial cost) to maintain compliance if the installed collection equipment failed.

The histogram which is shown in Figure 6 illustrates the predicted day-to-day emissions at Montour after ESP upgrading. The stack emissions are affected by five variables. The histogram includes the overlapping probability of multiple component failure. The variables, the ranges and the probabilities of occurence are listed below.

1. Boiler loading (historical)

750 MW	50%
700 MW	20%
650 MW	20%
400-500 MW	10%

2. ESP sections out of service

0 sections	90%
1 section	6%
2 sections	3%
3 sections	1%

3. Fuel ash content (dry basis)

Greater than 17% ash	5%
14% - 17% ash	50%
Less than 14% ash	45%

4. Fuel sulfur content

Less than 1% S	20%
Less than 1.5% S	60%
Less than 2.0% S	20%

5. SO_3 injection system

95% reliability (based on Commonwealth Edison experience)

The combined effect of the performance variables listed above results in a predicted compliance level of 96.5%. During the remaining 3.5% of the time, the units would have to operate at a reduced load to maintain compliance.

COST COMPARISON - MONTOUR UPGRADING VS. BRUNNER ISLAND 3 SERIES ESP

MONTOUR S.E.S. - 750 MW

Design criteria:

99.4% efficiency with 1.0% S coal with all equipment operating.

Compliance limit of 0.1 lb/MMBTU to be met 96.5% of time without forced load reductions.

Costs: (per unit)

Upgrading hardware (includes SO_3 system)	$ 4,000,000.
Annual O & M	$ 500,000
Annual forced load reductions	$ 1,000,000

BRUNNER ISLAND UNIT 3 - 750 MW

Design criteria:

Series ESP designed for 90% efficiency with 1.5% S coal. Existing ESP to operate at 95% efficiency for combined efficiency of 99.5%. SO_3 flue gas conditioning to be utilized with coals of less than 1.5% sulfur.

Compliance limit of 0.1 lb/MMBTU to be met 99+% of time without forced load reductions.

Costs:

ESP and auxiliaries (includes booster fans, SO_3 system, auxiliary transformer and site preparation)	$ 38,000,000
Annual O & M	$ 1,500,000

Approximately two-thirds of the annual O & M cost for the Brunner Island ESP is for electrical power for the new ESP and booster fans. It is interesting to note that the annual cost of power which will be used to operate the new collection equipment on Brunner Island Unit 3 is equal to the annual cost of the anticipated forced "compliance" load reductions at each Montour Unit.

RESULTS AND CONCLUSIONS

Since the upgrading at Montour was completed, the opacity on both units has been continually maintained in the 6% to 8% range even when as many as three ESP sections have been taken out of service. Figure 7 shows a comparison of opacity monitor charts during three phases of the Montour program. Note that the addition of TR sets and rappers in November, 1978 not only reduced the overall opacity but also greatly reduced the rapping spikes which were previously observed.

As of July 1, 1979, only Montour Unit 2 had been tested for particulate compliance. Preliminary results of the three emissions tests performed by the Pennsylvania Department of Environmental Resources indicated an average emission rate of 0.057 lb/MMBTU which is substantially below the allowable limit of 0.1 lb/MMBTU. (ESP efficiency is estimated at 99.6%). These tests are a positive indication that the Montour upgrading program has been successful in effecting a reliable, low cost solution to a problem which otherwise would have been resolved by the addition of expensive retrofit collectors.

Fly Ash Carryover

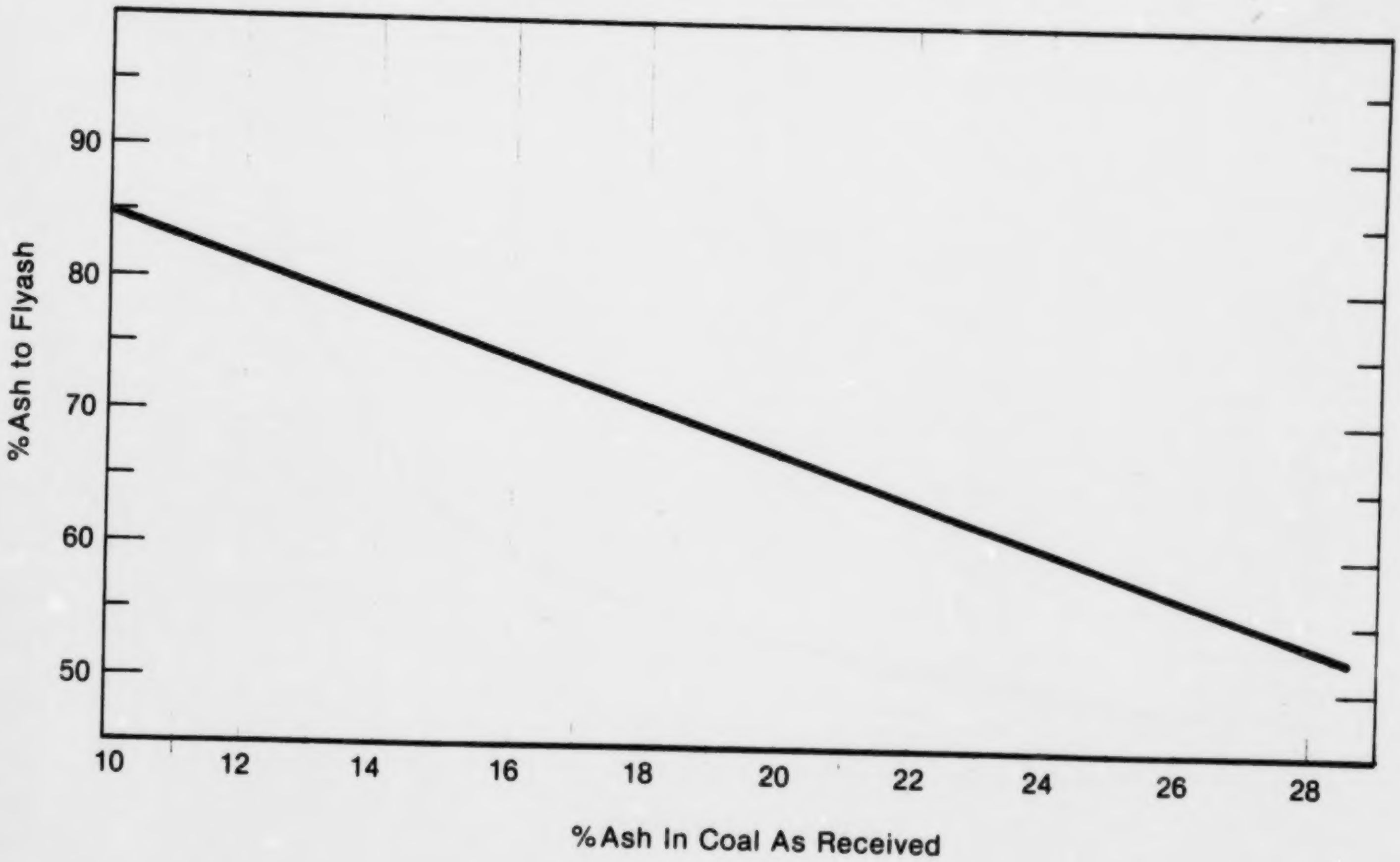


Figure 1

Required ESP Efficiency For Compliance

Chevron Units

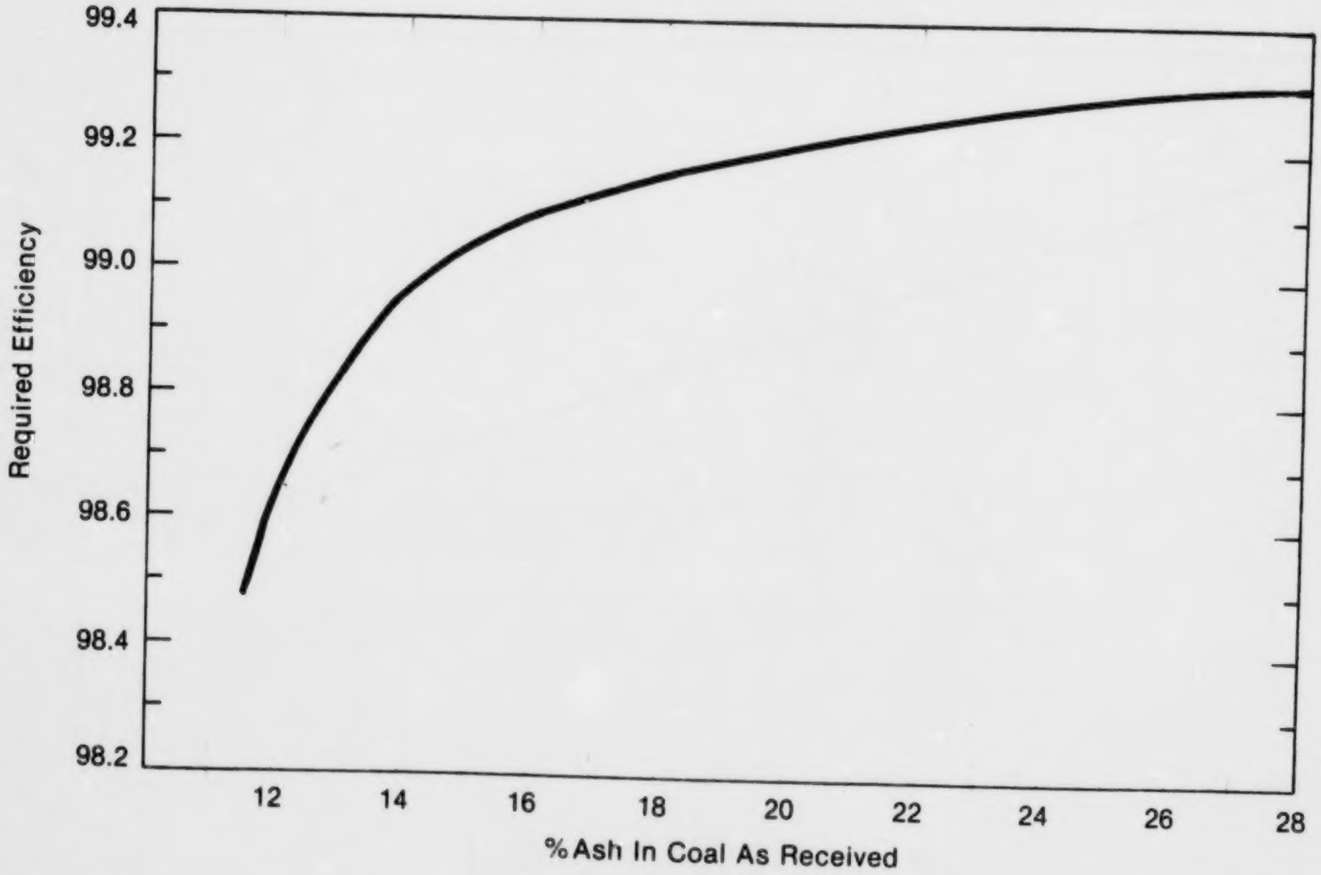


Figure 2

SUMMARY OF EFFICIENCY TEST DATA
BRUNNER ISLAND UNIT I

DATE	COAL TYPE	SULFUR %	ASH %	WAHLCO IN SERVICE	PRECIPITATOR EFFICIENCY		
					BUELL	R.C.	TOTAL
7/28/76	BENJAMIN	2.2	14.2	NO	92.8	94.7	93.6
7/29/76	BENJAMIN	〃	〃	NO	92.1	94.7	93.2
9/14/76	GREENWICH	1.0	12.1	YES-25PPM	93.3	96.1	94.5
9/15/76	GREENWICH	〃	〃	YES-25PPM	92.7	97.0	94.8
9/21/76	GREENWICH	1.0	11.5	NO	70.9	86.8	78.0
9/22/76	GREENWICH	〃	〃	NO	71.9	89.9	79.7

Figure 3

Montour
TR Set Modification

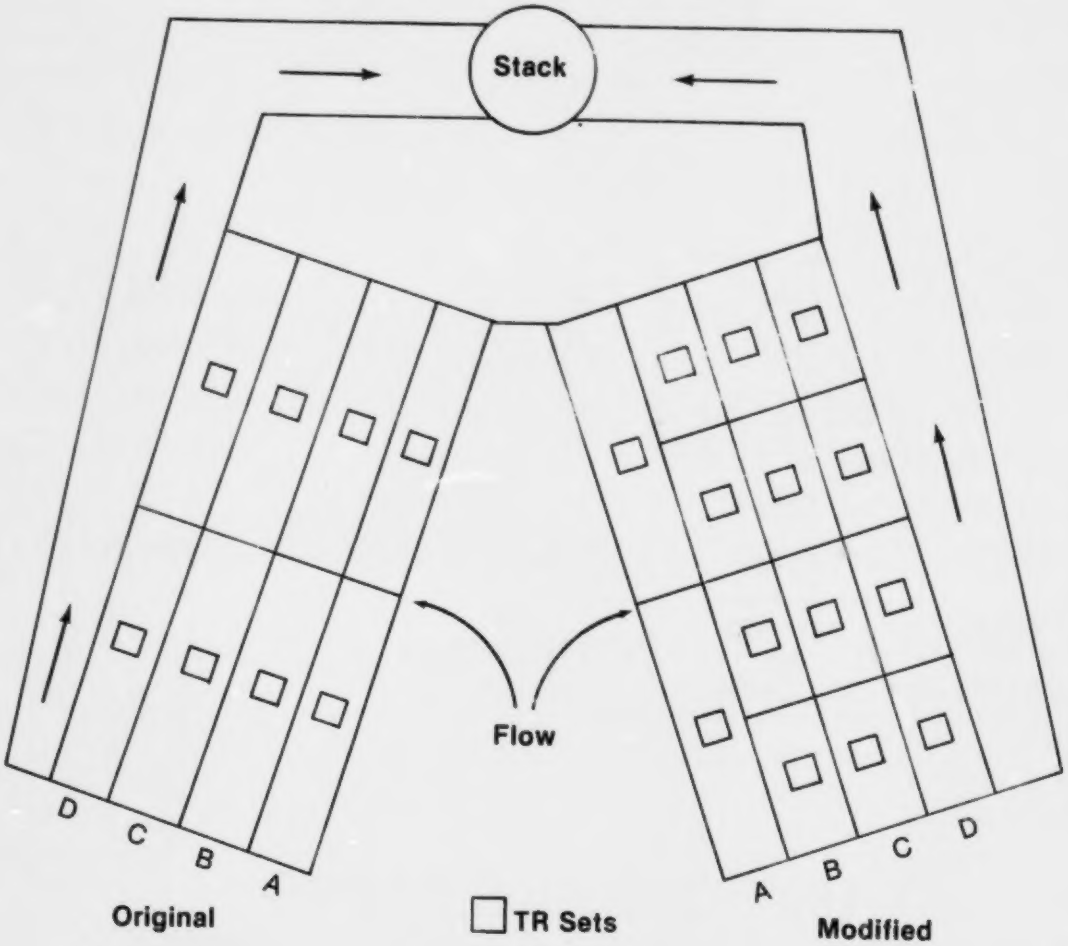


Figure 4

Montour S.E.S. Coal Control

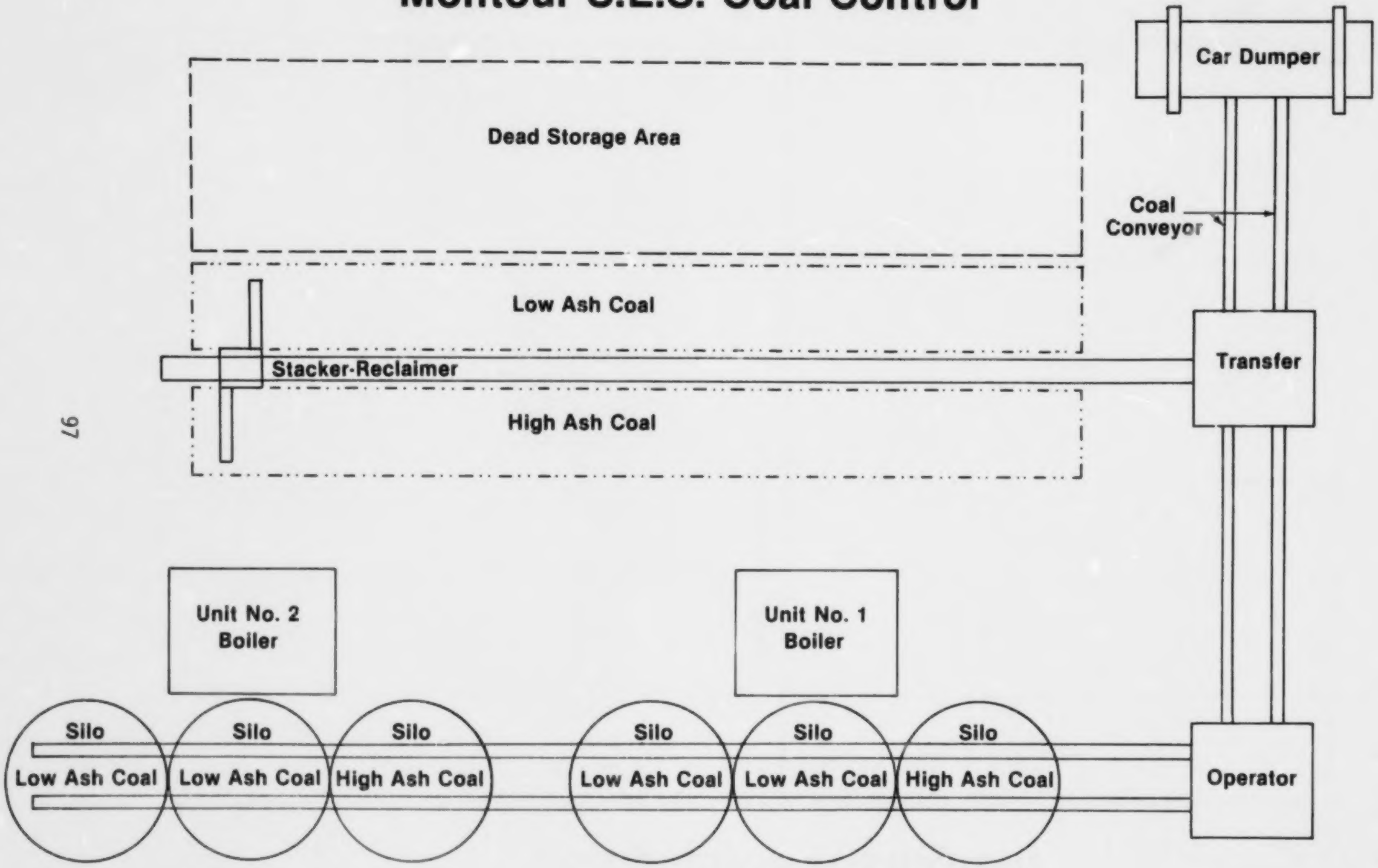


Figure 5

Compliance Histogram

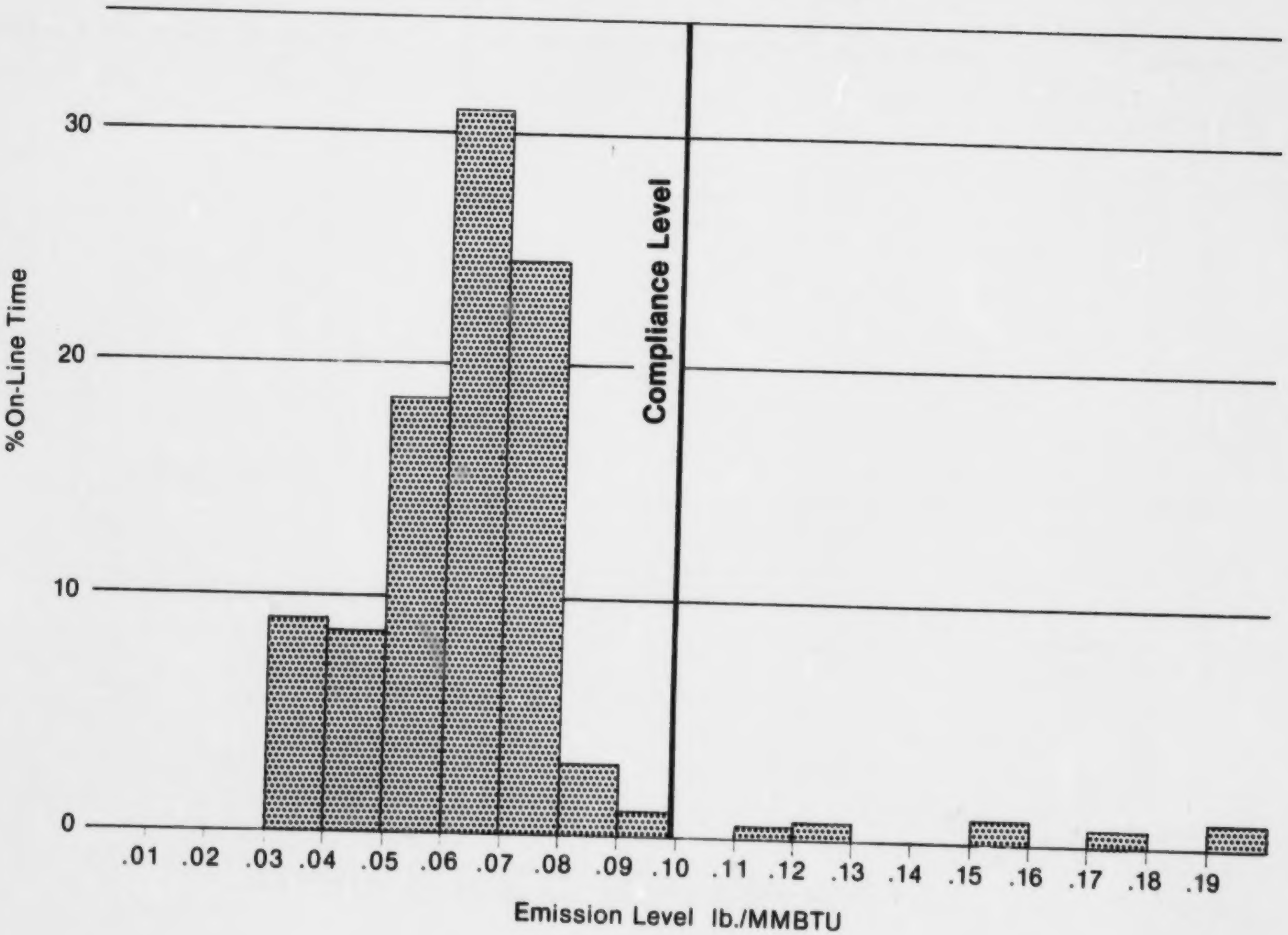
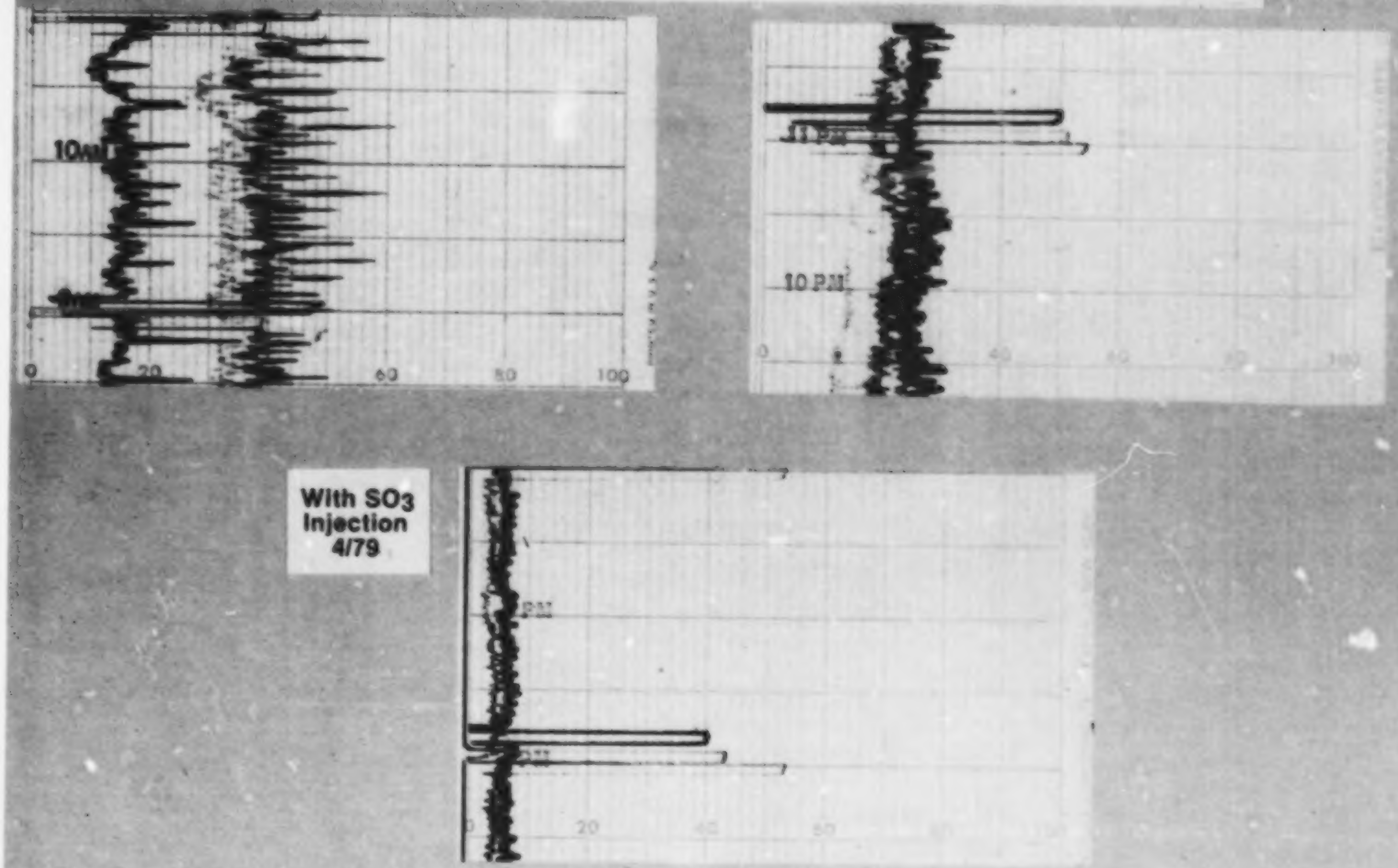


Figure 6

Opacity Comparison


Before Upgrading
6/78

After TR Sets and Rappers
11/78

With SO_3
Injection
4/79

Figure 7

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MODIFICATION OF EXISTING PRECIPITATORS TO RESPOND TO FUEL CHANGES AND CURRENT EMISSION REGULATIONS

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ABSTRACT

Practical improvements are presented for modifying existing precipitators to improve collection efficiency for high resistivity ashes from burning low sulfur coals. These modifications are also recommended as a foundation for other improvement programs such as temperature or ash conditioning.

The drive to reduce sulfur dioxide emissions has often been satisfied by burning coals with low sulfur content. The reduction in sulfur has in turn caused a marked reduction in the collection efficiency of electrostatic precipitators. Sulfur oxidizes upon combustion of the coal and forms SO_3, an important ash conditioning agent. Without it, efficiency deteriorates causing operators to turn to electrostatic precipitator vendors for recommendations.

There is no generally preferred solution. Replacement of the precipitator, ash conditioning, temperature conditioning and process modifications have all been successful. Each, however, involves a major commitment and has its drawbacks. It is felt that an alternative first step in responding to the need for improved performance of existing precipitators consists of modifying the precipitator to come closer to, if not to meet or exceed today's performance standards.

POSSIBLE SOLUTIONS

To demonstrate this approach, Figure 1 depicts typical trends in ash resistivity over a range of collection temperatures for coals of different sulfur contents. Although reduction in sulfur is generally detrimental to collection efficiency, the effect is most significant when the reduction is to a level of less than 1 percent sulfur. For example, a unit collecting 1.5 to 2.0 percent sulfur coal ash at about 150° C (point A) could show a ten-fold increase in resistivity if the coal sulfur content were decreased to below one percent (point B). Such a shift in resistivity is generally accompanied by a significant reduction in collection efficiency.

More common approaches attempt to reduce resistivity to a more manageable level by decreasing collection temperatures (point C), increasing collection temperatures (point D), or by fuel or flue gas conditioning (point E).

LOWERING RESISTIVITY

Operating the precipitator at decreased temperatures has been successful, however, this approach may require operating close to the dew point. This greatly increases the chances of condensation, corrosion, and fouling in the precipitator, air heaters, and ash removal system. When operating in this mode, particular attention must be paid to small changes in coal sulfur content which affects the acid dew point, and dictates how low one can drop the temperature. (1)

An alternative remedy that has been widely used to decrease resistivity is to operate the precipitator at the higher temperatures that are commonly found upstream of the air heaters. (2) It should, however, be a well studied decision to retire an existing "cold" side precipitator and install a new "hot" side unit.

Another approach that has shown success is the lowering of resistivity by fuel or fly ash conditioning. Operating costs should be compared to other alternatives as a possible deciding factor. Conditioning should not be categorically discounted. Work is continuing in the field and technically successful and cost-effective applications on difficult fuels have been demonstrated.

DEALING WITH HIGH RESISTIVITY

In addition to the three foregoing remedies which might decrease resistivity to a low or moderate level, an alternative may be to deal directly with the higher resistivities. This is not a popular approach because its application is limited and success is difficult to predict.

Despite this, circumstances exist where collecting a high resistivity dust is possible by upgrading existing hardware that was designed for a low resistivity ash. By reviewing precipitator design fundamentals, specific operating parameters can be picked out that are important in the collection of high resistivity ash.(4)

An example can be made of a small boiler that switched from 2.0% to 0.8% sulfur coal. The collection efficiency of its precipitator in turn dropped from 88 percent to below 60 percent (Figure 2). The corresponding precipitator power levels dropped from 60 to 30 watts/1000 acfm. After a modification program consisting of several of the changes discussed, power levels increased to 85 watts/1000 acfm and collection efficiencies are expected to be above the 90 percent level.

The following review of precipitator design theory shows how modifications can be chosen and how their individual contribution can lend to an overall improvement in precipitator performance.

SELECTING AREAS FOR MODIFICATIONS

Whether designed by analogy or by methods based on theory, the precipitator operation will generally follow the relationship given by the Deutch equation:

$$\eta = 1 - e^{-(A/V)\omega} \qquad (1)$$

where: η = probability of particle collection
A = collecting electrode surface area (ft^2)
V = gas flow rate (ACFS)
ω = migration velocity (ft/sec)

By increasing collecting electrode area A, by decreasing gas flow rate V, or by increasing migration velocity ω, collection efficiency η can be increased.

The first two options, increasing plate area and decreasing gas volume, involve major commitments that should only be contemplated after less severe options have been exhausted. Unless a spare precipitator bay already exists for additional plate area, or derating of the boiler is acceptable, these alternatives are not the most desireable.

The remaining variable ω, or migration velocity, thus, becomes the prime target for improvement. Migration velocity is synonymous with precipitation rate for ideal uniform conditions of particle size, gas velocity, etc. Because these ideal conditions do not necessarily exist in actual operation, an effective precipitation rate parameter ω_e is used instead.(5) The most important variables that affect ω_e are:

1. Fly ash resistivity
2. Particle size distribution
3. Gas velocity distribution
4. Reentrainment
5. Gas sneakage
6. Rapping conditions
7. Electrical conditions

Resistivity and particle size distribution are given conditions whose range of values should be reasonably well established for actual or anticipated boiler operating conditions. Each is measurable if a test burn of low sulfur coal is planned as part of a modification program. This is strongly recommended, since source test data collected during a preliminary burn will help identify potential problem areas and form a basis for modifications. Improvement of the five remaining variables that affect ω_e can be addressed from the standpoint of precipitator modifications.

Gas Velocity Distribution

Precipitators that are 15 or more years old may not have been engineered to meet specific gas velocity distribution criteria such as provided by the IGCI. With increasingly higher levels of required efficiency over the past years, more importance has been placed on obtaining flow patterns that are as uniform and ideal as feasible. Beginning with a cursory review of the installed flue work and gas distribution system, an evaluation of the need for improvement can be made. Some units, for example, have potentially more collection plate area available if gas distribution were improved.(6)

A reliable method of determining the need for improvement is to measure the velocity distribution at the inlet and outlet of the precipitator as well as in the gas passages between collecting electrodes. When this information is compiled, it is often combined with a model study program, in which a 1/16 scale model is built representing the precipitator and its related ductwork. By installing various baffles, turning vanes, etc., numerous configurations for improving the flow profile can be tested at a fraction of the full-scale cost.

Whether from model or from field data, enough information can be evaluated to determine if modifications to gas distribution will improve ω_e and hence precipitator performance.

Reentrainment

Among the problems addressed by a gas distribution study is reentrainment. Reentrainment is generally referred to as dust that returns to the gas stream after collection rather than leaving via the ash removal system. It occurs mainly as a function of four things: gas flow, particle characteristics, electrical energization, and rapping. Reentrainment due to gas flow should be corrected by modifications to the existing ductwork as specified by the model study or distribution study.

Dust properties are a function of upstream conditions, so precipitator modifications should not affect dust properties beyond altering the pattern of selective collection as the dust moves through the unit. The remaining variables that affect ω_e are then rapping and electrical energization.

Rapper System Modifications

Resequencing of individual raps, and varying rapping intensities and time cycles can minimize reentrainment. Of equal importance is the necessity to keep collecting electrodes as clean as possible. It has long been established that the non-conductive properties of high resistivity dusts impair precipitator current flow and are readily suspect in causing back corona once resistivities are 10^{10} ohm-cm or more.(5) Rather than reiterate the principles involved, it is sufficient to note that back corona and reduced performance often occur when too much high resistivity dust has accumulated on the collecting electrodes. The important point is to keep dust accumulations to a minimum so that current flow will not be impaired and the breakdown voltage of the dust layer will not be met. Although back corona can occur for a lower resistivity dust, substantially more ash must be accumulated before the phenomenon is encountered. This is evident from the Ohm's law relation:

$$\Delta V = J\rho t \qquad (2)$$

where: ΔV = sparkover voltage (volts)
J = corona current density through the ash layer (A/cm^2)
ρ = resistivity (ohm-cm)
t = thickness of the layer (cm)

Breakdown voltages for most dust are on the order of 10 to 20 kV/cm.(5) In Figure 3, Ohm's law has been used to show graphically how substantial accumulations of high resistivity dust on the collecting electrode could produce a voltage drop across the layer that exceeds the usual range of breakdown voltages if the current is hypothetically unsupressed by sparking and assumed to be constant. If such currents were feasible, a 0.5 cm accumulation of 10^8 ohm-cm dust should show a voltage drop of less than 5 kV. When 0.5 cm of 10^{10} ohm-cm dust is accumulated, however, the voltage drop should be well in excess of the breakdown field of 10 to 20 kV, and back corona will likely ensue. It should be apparent that collecting electrodes need to be cleaner than on moderate or high sulfur coal applications, and because of the strong dipolar attachment of the dust, effective rapping is needed for high resistivity dust, otherwise current density will be lower than is already necessary to avoid back corona.

Rapper systems designed for high sulfur coals were adequate for the job required. Collecting electrodes were often rapped only on their leading edges at nominal intensities and at rather lengthy time intervals. To meet the increased demand associated with high resistivity dust, operators have often resorted to more intense and more frequent rapping cycles. As might well be expected, this can substantially reduce the operating life of the rapping system. (7)

Proper modification of the existing rapping system can greatly improve reliability and effectiveness. Areas to consider are the rapper, the transmission hardware, and the rapper controls.

Rapper Assembly - The rapper assembly should be reliable for its new duty cycle. Because numerous types and models are available, it is difficult to pinpoint specific required modifications. Another concern is useful rapper energy. Many rappers installed over the past decade are capable of delivering the required higher energies. The question is whether or not operation at the high end of their capabilities under more frequent time cycles can be reliably sustained. All available modifications should therefore be considered to build in required rapping power and reasonable reliability.

Transmission Hardware - The increased demand on the rapper itself can be substantially reduced by modifying the rapper transmission hardware. By the time energy from a single rap is delivered to its applied area of collecting electrode, it will often have traveled through a tortuous path with substantial energy losses. Through proper modification, the losses can be reduced and more energy delivered to the plates. A typical rapping transmission system that can be upgraded is shown in Figure 4. The rapper impact is transmitted via a rapper rod through the penthouse roof and floor to a striker assembly attached to the collecting electrode support member.

To reduce failures under demanding low sulfur coal operation, the quality of the striker block connection can be improved.

Typical connections used are butt welds to anvil beams or welded cup assemblies (Figure 5). In either case, the amount of available weld surface between the rapper rod and the anvil system is minimal, with multiple welds required for assembly. An improvement is the gusset joint which requires little field welding and can remain functional even if the critical weld between the rapper rod and striker block fails. An added advantage to the gusset joint is the more uniform distribution of rapping energy along the electrode support member. This permits outboard electrodes a better chance receiving their share of the rapping energy.

Replacement of older seals with newer designs can reduce the possibility of binding. Newer seals can be chosen that do not need periodic repacking. Others have been designed to reduce seizure in the seals due to corrosion. To reduce further energy loss and promulgate even distribution, the electrode support system can be reinforced (Figure 6). The rapper impact is delivered to the collecting electrode through a tube support that rests upon the electrode support beam. By reinforcing the plate support tubes with a stiffening member, more even distribution is achieved across the top of the collecting electrode.

To complete transmission modifications, the trailing edge of the collecting electrodes should also be supplied with a rapper and the same modifications as shown for the leading edge. As mentioned earlier, the tube member rests upon the electrode support member, and in some cases only one edge of the plate was secured to the support member. By securely welding both edges one can improve the transmission of rapped energy without impairing precipitator reliability.(8)

Rapper Control - A rapper control sequences rapper timing and energizes individual rappers. A breakdown in either area will eventually disrupt precipitator performance, especially on a low sulfur coal operation. Particularly vulnerable to this type of malfunction are those controls which incorporate mechanical switching and sequencing. Where these are used, malfunctions will occur primarily in contact assemblies because of arcing or mechanical wear. Arcing and wear of both sequencing and switching contacts is enhanced by poor contact closure, poor timing, and rapper ground fault conditions.

The use of more reliable solid-state devices is recommended for substitution of the above mechanical system where operating voltages permit. In addition to increased reliability, solid-state controls permit continuous on-line monitoring of system operations. Where a faulty rapper used to cause control damage, the newer systems will test individual rappers before energization and bypass them if they are defective. The defective units will be displayed on the control panel, thereby permitting easy location during maintenance periods.

Electrical Conditions

Thus far most of the areas that affect ω_e and precipitator performance have been covered. The remaining area of electrical energization is dealt with last because of its complexity and importance. In Equation (1) it was shown that an increase in drift velocity or its operating equivalent, ω_e, would result in an increase in precipitator efficiency. Precipitation rate ω_e may be related to the corona power by the relation

$$\omega_e = K_1 \, Pc/A \qquad (3)$$

where K_1 is a parameter characteristic of the given ESP in its application and Pc/A is the corona power density in watts/ft^2 of collection surface. It follows that if modifications can increase corona power, efficiency will benefit. Improvements in electrical energization can be obtained by modifying several areas.

High-Tension Sectionalization - In theory, as well as in practice, optimum collection is achieved by applying maximum peak and average voltages while losing as little power as possible to sparkover conditions. It is therefore important to match the corona level of each relatively small corona section to the dust characteristics in that section. This is most commonly achieved by minimizing the number of discharge wires associated with individual voltage supplies and their controls. Adequate high-tension sectionalization is also important from the standpoint of sparkover. The more often sparkover occurs in a particular high tension section, the more power will be lost and not be used for collection. By increasing sectionalization, the detrimental effects of individual sparkovers can be contained in relatively small sections of the precipitator, thereby increasing peak voltages. This is especially important when dealing with high resistivity dusts because of the greater tendency toward sparking and difficult charging characteristics. Sectionalization should, therefore, be carried out not only in the direction of gas flow to compensate for changing dust properties, but also across the gas flow, to minimize the problems of sparkover. In Figure 7, examples of increased sectionalization in series and parallel to gas flow are shown.

Voltage Wave Shape - The faster a voltage supply control can respond to a sparking condition, quench the spark, and restore power to the precipitator, the better are the chances of increased power usage and increased collection efficiency. As with rapper controls, solid-state logic systems have found a natural home in the electrostatic precipitator. Accurate, fast responding systems are available with power recovery times of only one or two cycles after quench. Modifications in this area often include use of state-of-the-art rectifiers and controls, linear inductors for improved waveform control, and fast acting feedback networks that trigger the automatic voltage control systems.

SUMMARY

There are numerous areas for potential improvement of the performance of existing precipitators. It is well recognized that the modifications described are not applicable or feasible in all cases of existing units, however, the discussion points out that given certain conditions, the modifications may improve performance on high resistivity ash to an acceptable level. In addition, they should be considered first to improve overall performance, regardless of any other plans for increasing performance via process changes or conditioning systems.

REFERENCES

1. Oglesby, S., and Nichols, G.B. "Electrostatic Precipitation." Marcell Dekker, Inc., N.Y., N.Y., 1978 p. 134.

2. Walker, A.B. "Hot-Side Precipitators." APCA Journal, Vol. 25, No. 2:144, February, 1975."

3. Brennan, J.H. and Reveley, R.L. "Flue Gas Conditioning with SO_3 to Improve Precipitator Performance." Proceedings of the American Power Conference, 1977.

4. Panev, S.N. et al. "The Problem of Collecting Dusts that Cause Reverse Corona Formations in ESP's." Proceedings of Second US/USSR Symposium on Particulate Control. EPA, March, 1978.

5. White, H.J. "Electrostatic Precipitation of Fly Ash." APCA Reprint Series, July, 1977. p. 17, 48.

6. Bump, R.L. "Electrostatic Precipitators in Industry." Chemical Engineering, January 17, 1977, p. 133.

7. Lynch, J.L. and Kelly, D.S., "A Review of Rapper System Problems Associated with Industrial Electrostatic Precipitators." Proceedings of Operation and Maintenance of ESP's, APCA, April, 1978, p. 48.

8. Unpublished information from authors files.

FIGURE 1 OPERATION DEPENDENT RESISTIVITIES

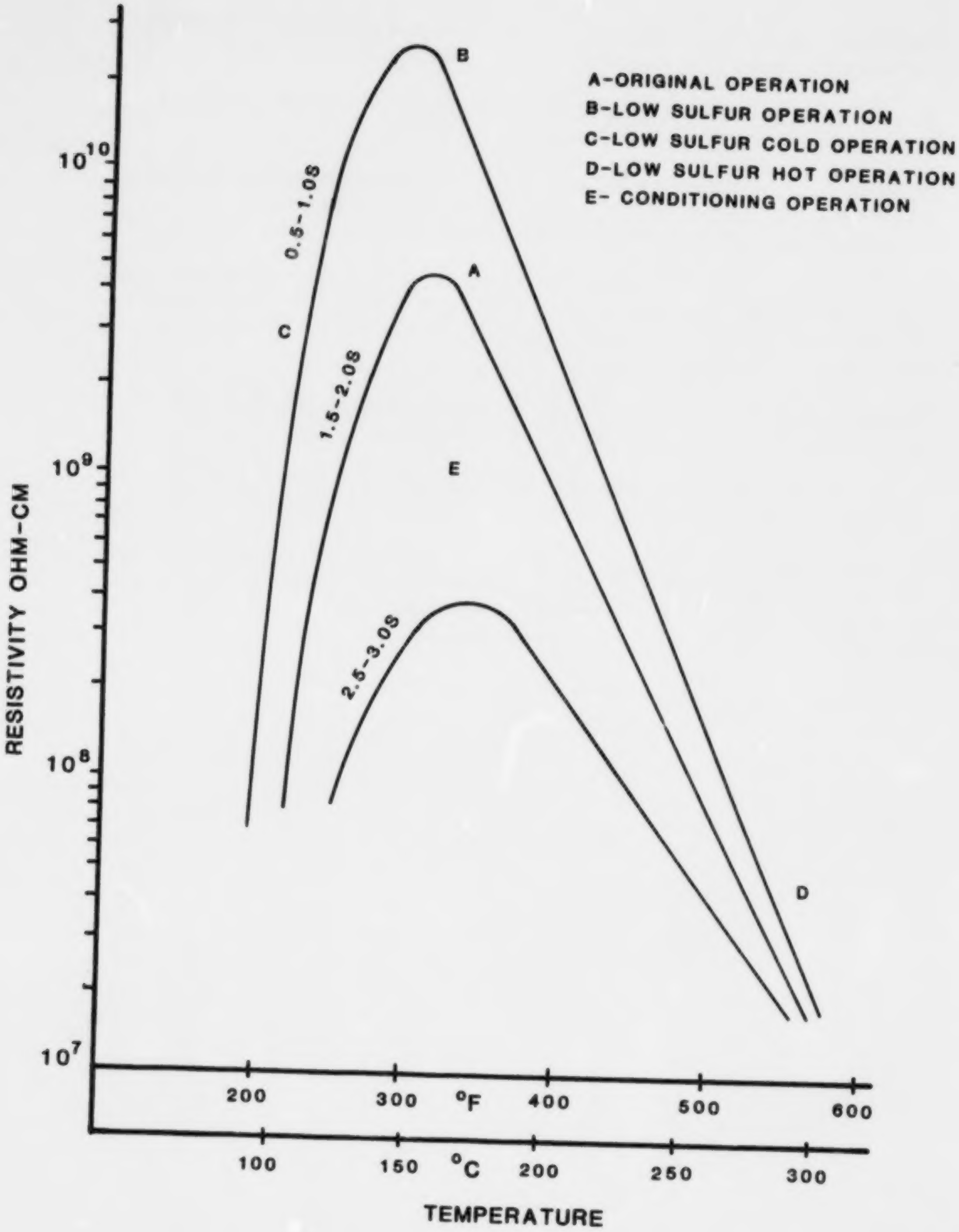


FIGURE 2 ESP COLLECTION EFFICIENCY VS. CORONA POWER DENSITY (Pc/V)

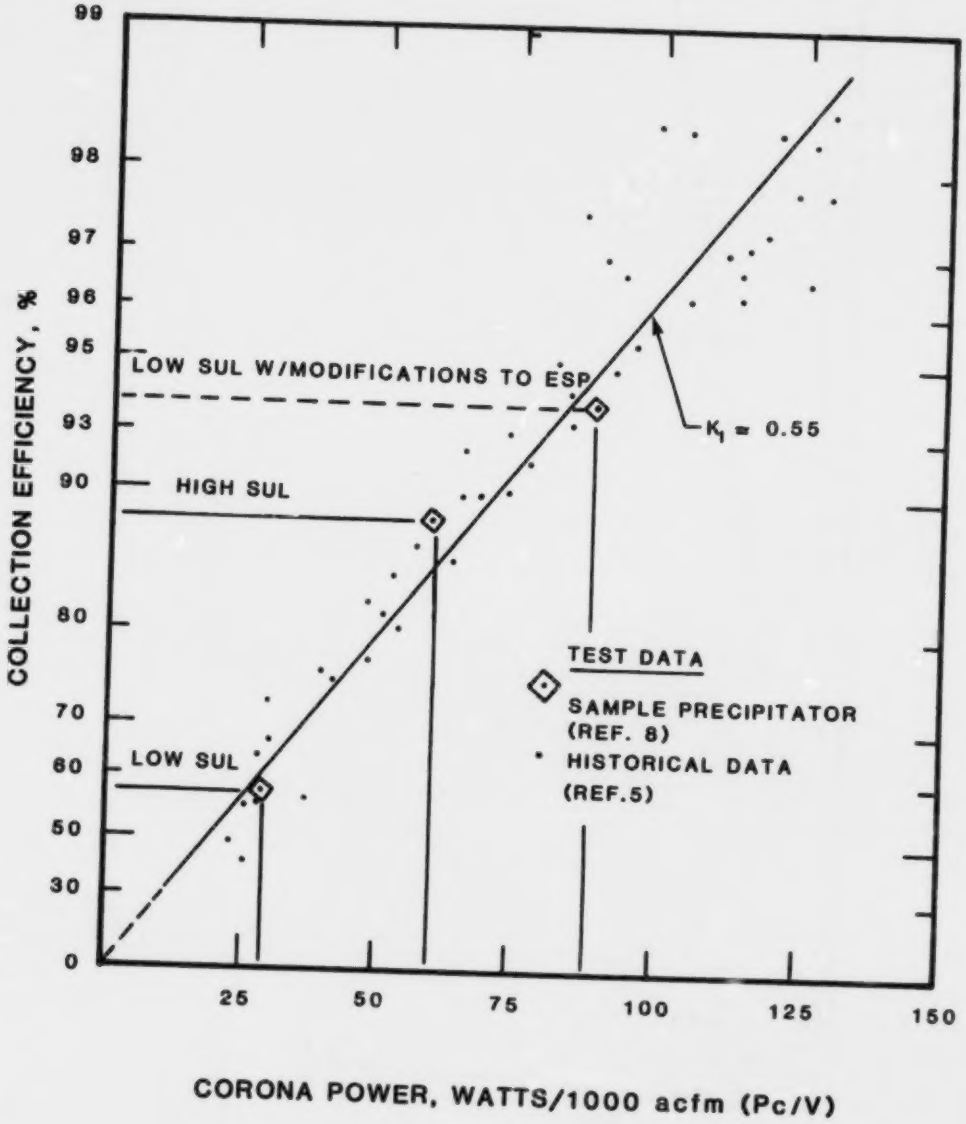


FIGURE 3 EFFECT OF ASH THICKNESS ON VOLTAGE DROP FOR VARIOUS ASH RESISTIVITIES

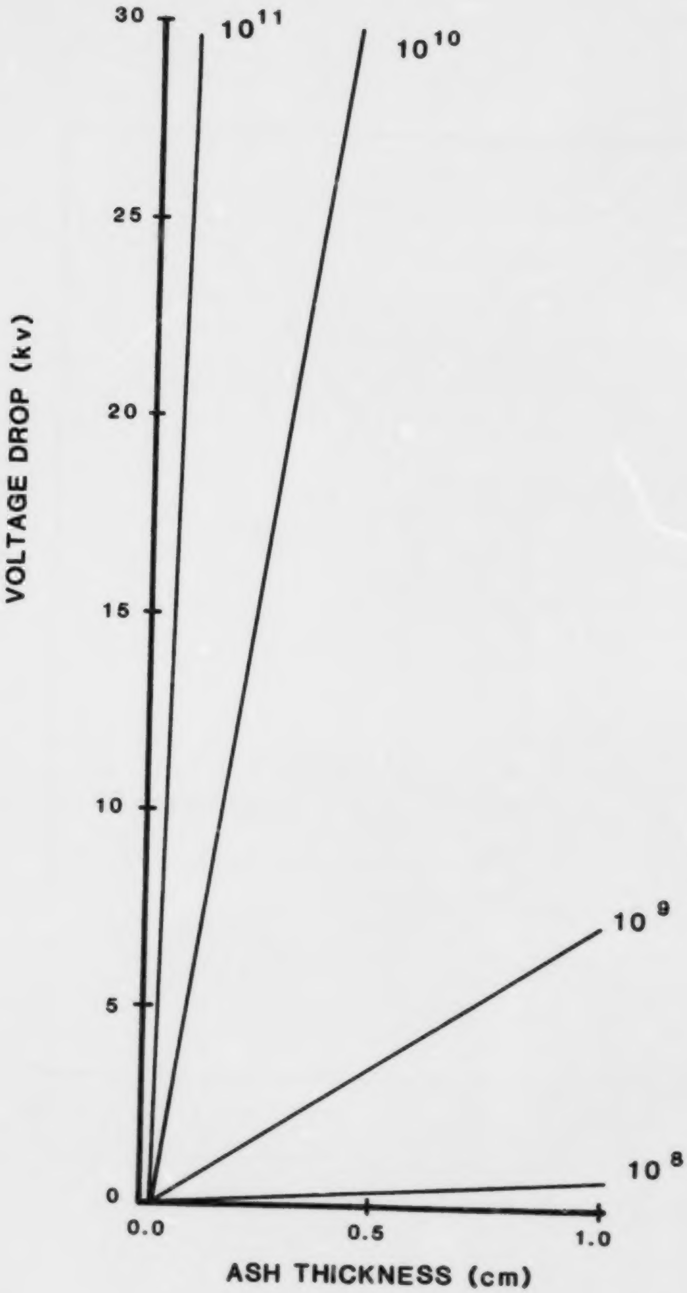


FIGURE 4. TYPICAL COLLECTION ELECTRODE RAPPING SYSTEM ON OLDER PRECIPITATOR

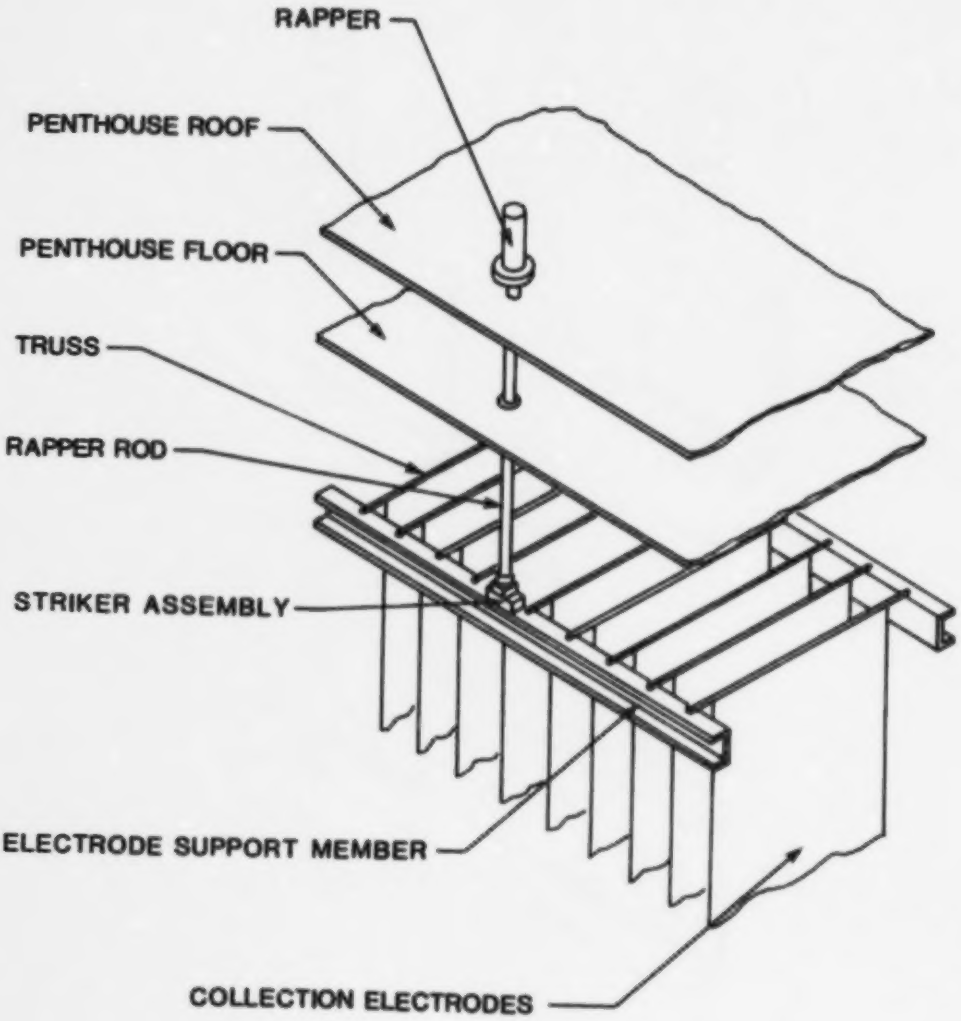


FIGURE 5 RAPPER BAR CONNECTIONS

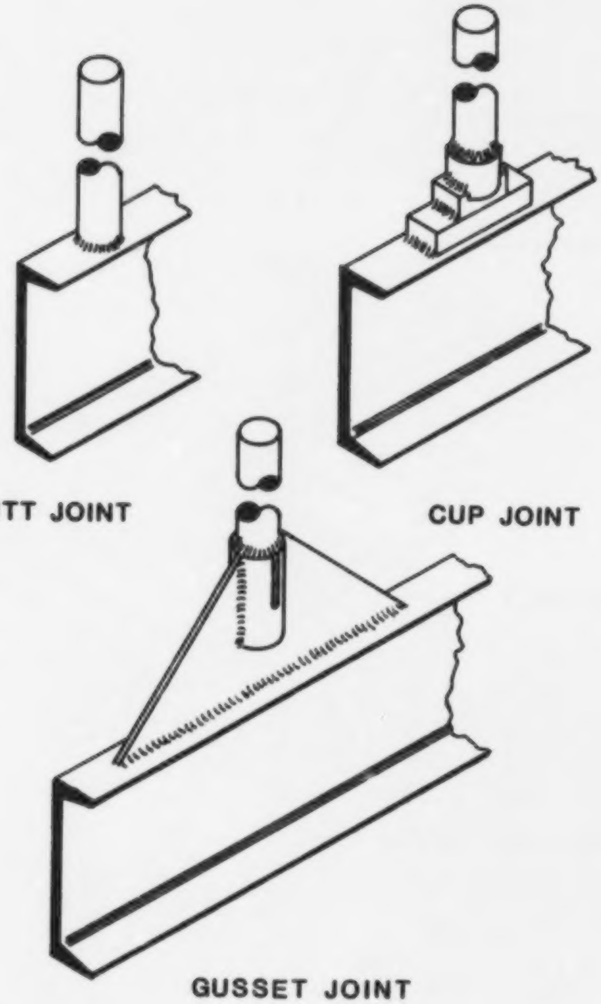


FIGURE 6 MODIFIED COLLECTION ELECTRODE RAPPING SYSTEM ON OLDER PRECIPITATOR.

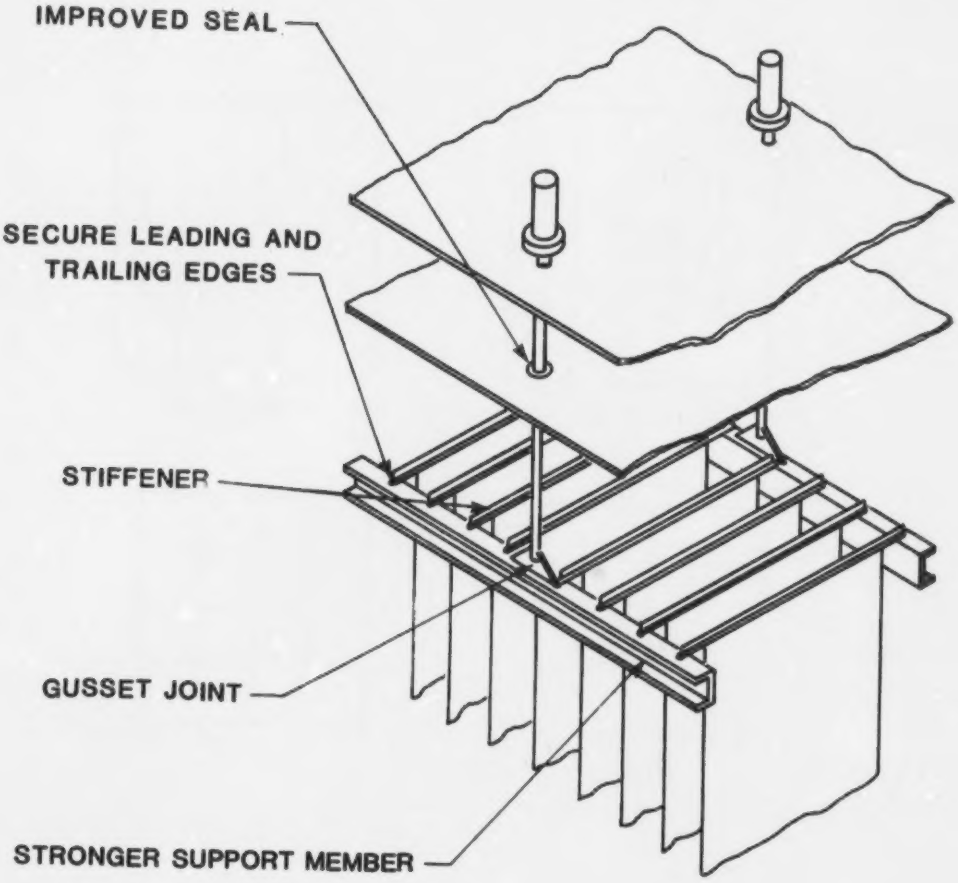
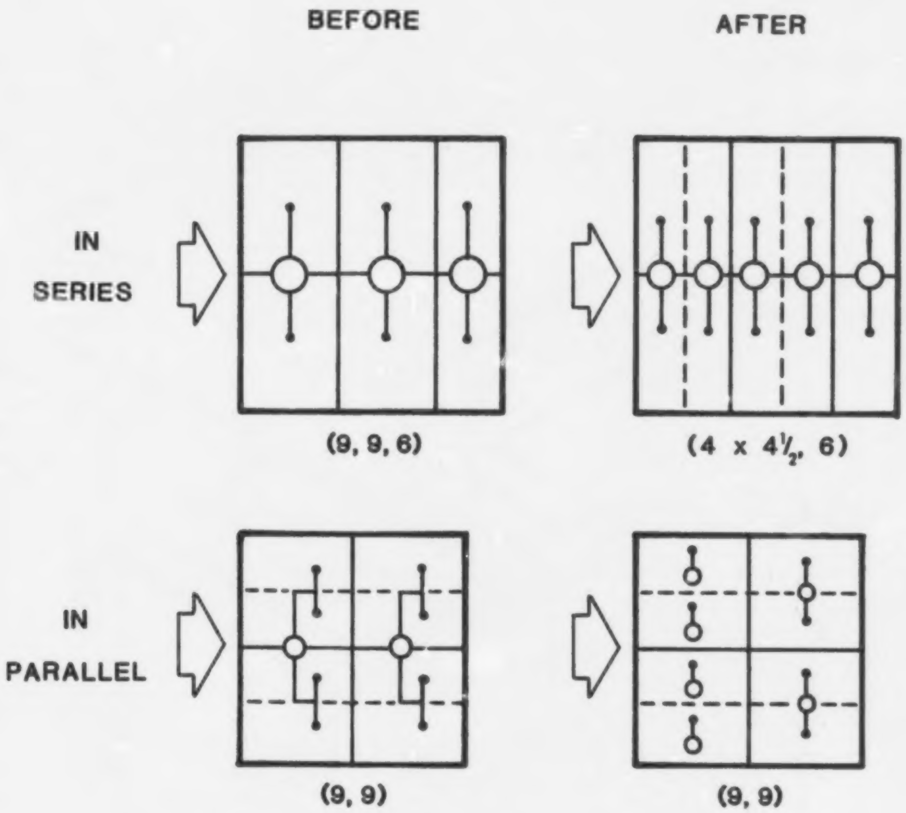


FIGURE 7. EXAMPLES OF MODIFICATIONS TO INCREASE SECTIONALIZATION



PERFORMANCE OF ELECTROSTATIC PRECIPITATORS WITH LOAD VARIATION

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ABSTRACT

The load variation performance of electrostatic precipitators has been characterized through a field test program. The test program results indicate significant differences between cold-side and hot-side electrostatic precipitators.

Hot-side precipitators have been found not to follow the expected Deutsch-Anderson relationship with load variations. Various mechanisms are postulated and are validated or rejected, based upon the results from the test program.

The test program included measurement of chemical analysis of the coal source, the inlet and outlet particulate loading, resistivity of the dust, particulate size distribution and chemical analysis of the dust samples.

PERFORMANCE OF ELECTROSTATIC PRECIPITATORS WITH LOAD VARIATION

INTRODUCTION

The performance of electrostatic precipitators has been traditionally described by the modified Deutsch-Anderson relationship (Reference 1).

$$\eta = 1 - e^{-(\omega . SCA)^k}$$

where e = natural logarithm
k = non-dimensional constant
SCA = specific collection area
η = precipitator collection efficiency
ω = migration velocity

The K value in the classic Deutsch equation has a value of one; whereas, recent analysis has K values between 0.5 and 0.75, Reference 2. This formulation has been made to reflect the decreasingly effective migration velocities at the higher collection efficiencies because of the decreased ability of the precipitator to collect the increasingly finer particulates.

The Deutsch-Anderson formula predicts the precipitator performance to increase with decreasing load conditions due to the reduced gas volume. This expected behavior has been typically experienced with cold-side electrostatic precipitators. For instance, the precipitator performance with load variation is presented in Figure 1, see Reference 3.

PERFORMANCE OF HOT-SIDE ELECTROSTATIC PRECIPITATOR WITH LOAD VARIATION

The performance of two hot-side electrostatic precipitator units with load variation is shown in Figure 2. These data clearly demonstrate that the precipitator performance can decrease with load reduction. This relationship of decreased precipitator performance with reduced load is inconsistent with the performance expectations from the Deutsch-Anderson equation.

Plant A, depicted in Figure 2, is a 99.1% efficiency precipitator burning South African coal; whereas, Plant B is a 99.0% efficiency precipitator using primarily Hazard, East Kentucky coal. The analysis of the coal from these two plants is shown in the following table:

COAL SOURCE

Parameter	Plant A	Plant B
Moisture	5.95	2.69
Ash	13.93	10.49
Total Carbon	68.47	74.23
Sulfur	0.71	0.72
BTU/Pound	11,500	12,600

The operating conditions for the precipitator at the two plants are presented in the following table:

Operating Conditions	Plant A	Plant B
Megawatt Production at Full Load	195	~450
Flow Rate at Full Load (ACFM)	1,021,000	2,537,000
Flow Rate at Half Load (ACFM)	762,500	1,395,000
Temperature at Full Load (°F)	700	643
Temperature at Half Load (°F)	575	529

Thus, although these units are burning considerably different coal, as well as having different operating conditions, these units clearly indicate decreased precipitator performance at reduced loads.

The following mechanisms were postulated as potential explanations for the degraded precipitator performance with decreasing load:

- High resistivity problem at the lower load condition due to decreased temperature.
- Particle-size distribution change at the lower load boiler operation.
- Flue gas properties change at the lower load boiler operation.
- Dust dropout at low load which is picked up with increasing load; thereby, overloading the precipitator.
- Increase in precipitator inlet loading during low load boiler operation.
- Poor gas flow distribution at low load condition.

Tests were conducted to determine which of the hypothesized mechanisms were responsible for the degraded performance at reduced load. A test program included measurement of the inlet and outlet particulate loading, resistivity of the dust, particulate size distribution and chemical analysis of the dust samples at different load conditions.

Four tests were conducted at Plant A under reduced load conditions. Two were conducted at stable three-quarter load conditions and two were performed during transient condition from low to full load conditions.

The efficiencies obtained from these tests are compared with the corresponding values for full load condition in the following table:

Condition	Efficiency %	Volume, ACFM
3/4 Load	99.0	1,000,000
Transient	94.5	920,000
Full Load	99.5	1,030,000

The efficiency for both the 3/4 load and transient load condition are lower than at the full load condition. The performance at the transient condition is dramatically below the full load performance.

The inlet loading and corresponding emissions for these conditions, along with the design values, are the following:

Condition	Inlet Loading Grains/SCF	Emissions Grains/SCF
3/4 Load	6.47	.06
Transient	13.1	.7
Full Load	6.5	.02
Design	4.98	.04

The inlet loading for the transient load condition is much higher (greater than factor of two) than the corresponding design value. The inlet loading's full load and 3/4 load are nearly identical and are slightly higher than the design value.

The inlet median particle size and resistivity for the conditions are the following:

Condition	Inlet Median Particle Size, Microns	Resistivity Ohm/CM
3/4 Load	11	2 x 10^9
Transient	16	8 x 10^9
Full Load	11	1 x 10^9

The inlet median particle size measured during transient condition is larger than either the 3/4 load or full load condition. This could result from either a change in boiler operation or dust being swept up from the ductwork when the load is increased. The measured increased inlet dust loading under transient conditions would also support these hypotheses. The performance degradation during decreasing load conditions would be caused by different mechanisms.

The resistivities presented in the previous table are at the temperature corresponding to the load condition. The temperature at the 3/4 load is well characterized and does not have a large spread: 617°F to 646°F. The temperature spread during the transient load condition is quite large: 569° F to 679° F. The resistivities were measured in the laboratory. Previous studies on other precipitators have indicated that resistivities determined by in-situ and laboratory measurements are in reasonable agreement at high temperatures. The resistivity-temperature dependence for the transient and 3/4 load conditions are shown in Figure 3. These data demonstrate that the resistivities do increase at the lower temperatures associated with the low loads. The resistivities at low load would not be expected to cause precipitator problems. The critical resistivity for back corona initiation associated with hot-side precipitators is suspected about the order of magnitude lower than for the cold-side unit.

The comparison between the resistivity for the transient load condition appears to be higher than corresponding resistivity at 3/4 load condition for a given temperatures.

This suggests there could be a difference in flyash characteristics between transient and 3/4 stable load. In order to assess this effect, a comparison of the chemical properties of the inlet flyash for the transient load and 3/4 load conditions was made and is presented in the following table:

Condition	LOI	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Transient	11.22	37.13	3.77	28.85	5.63	2.26
3/4 Load	12.34	36.49	3.01	26.81	5.05	2.17

Condition	SO_3	TiO_2	K_2O	P_2O	Na_2O	Li_2O
Transient	2.25	3.93	0.30	0.75	0.35	0.06
3/4 Load	2.17	3.54	0.29	0.83	0.30	0.06

A comparison of this data does not indicate a significant difference in the flyash properties due to boiler operation.

The hypothesized mechanisms are reviewed with the findings from the test program in the following table:

MECHANISM	FINDINGS
Dust Dropout	● Extremely high inlet loading measured during transient condition. ● Particle size data for transient condition higher than stable load. ● Mechanism could not be cause of performance degradation from high load to low load transient.
Particle Size Distribution of Flue Gas Properties Change at Lower Boiler Operation	● Present data does not support this hypothesized mechanism. ● Little data available at low load to totally disqualify this mechanism
High Resistivity Problem at Partial Load	● Transient resistivity appears higher than 3/4 load. ● However, 3/4 load resistivities lower than previous full load data.
Plate Dust Buildup	● Additional plate buildup probable during transient loads due to high inlet loadings.
Poor Gas Flow at Low Load Condition	● No data on this unit. ● Model study data on other units do not support this hypothesized mechanism.
Power Loss Due to Inability of Controls to Respond to Transient Conditions	● Controls have adequately responded to transient load conditions.

Based on these results, the main contributions due to the degraded performance at low load are:

- High inlet particulate loading
- High resistivity problem at partial load
- Aging of dust material on collecting plates.

The aging of dust material on collecting plates is described in the next section.

HOT-SIDE ELECTROSTATIC PRECIPITATOR LONG-TERM PERFORMANCE DETERIORATION

Several hot-side electrostatic precipitator units have experienced a performance deterioration after several months of operation. This has been most pronounced with units operating with low sulfur fuel, such as Western coal.

The precipitator unit at Plant A, described in the previous section, exhibited this type of long-term performance deterioration. After several months of operation, the unit's collection efficiency of 99.5% and corona power level of 204 kilowatts decreased to a collection efficiency of less than 99% and a corona power level of 110 kilowatts.

A detailed internal inspection of the unit indicated that ash buildup on the collecting plates consisted of two distinct layers: an outer layer of gray, fluffy material, and an inner layer (adjacent to the plate) of white crusty material. The thickness of the inner layer was approximately 1/16 inch; whereas, the outer layer thickness was approximately 1/8 inch.

The inner layer, presumably, is older residue ash not removed by rapping; whereas, the outer layer is collected transient ash, rapped free, and replaced by newly-collected ash.

The precipitator performance degrades after several months operation; presumably, from change in the inner layer properties. The residue dust layer not removed by rapping undergoes alteration in properties with age.

It was postulated that the inner layer significantly increases in resistivity with time. This change could be induced by thermochemical or electrochemical reaction.

Analysis was performed with the inner and outer layer dust samples to discern the differences between the inner and outer layer properties, as well as to determine if the change was primarily a result of thermochemical or electrochemical reaction.

Flyash Analysis

Samples of each layer, as well as dust samples from the emitting wires, were obtained during the internal inspection for chemical analysis. These samples were obtained from two similar precipitator units operating on similar boilers with the same fuel source. The results of the chemical analysis of these dust samples are presented in the following table:

CHEMICAL/ANALYSIS OF FLYASH

Sample Description	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	CaO	MnO	Na_2O	K_2O	Li_2O	P_2O_5	SO_3
Inner Plate Layer Plant A, Unit #1	35.5	28.8	1.42	6.76	2.08	7.34	0.11	0.42	0.73	0.050	2.52	9.1
Outer Plate Layer Plant A, Unit #1	39.2	33.3	1.64	4.02	2.40	7.32	0.11	0.37	0.51	0.067	2.58	4.2
Inner Plate Layer Plant A, Unit #2	34.1	28.3	1.35	8.00	2.16	7.00	0.11	0.36	0.48	0.045	2.34	11.1
Outer Plate Layer Plant A, Unit #2	39.2	33.9	1.61	3.57	2.41	6.98	0.08	0.43	0.55	0.067	2.64	4.1
Wire Sample Plant A, Unit #1	42.1	33.4	2.41	4.08	2.45	5.50		0.46	0.36	0.08	1.23	3.6
Wire Sample Plant A, Unit #2	42.1	34.3	2.26	3.73	2.48	5.57		0.39	0.36	0.07	1.10	2.55

The inner and outer layer differ most significantly in their Fe and S content. Identical samples of the inner and outer layer were analyzed by two independent analysts. The results from both analyses show the significant difference in the Fe and S content between the inner and outer layer. It is likely that the inner layer is formed by a chemical reaction among the SO_2, SO_3 in the flue gas and the plate:

$$SO_2 + 1/2\ O_2 \rightarrow SO_3$$

flyash
catalyst

$$\frac{X}{2}O_2 + X\ SO_3\ X\ Y\ H_2O + Fe \rightarrow$$

$$Fe\ (SO_4)_x\ Y\ H_2O$$

X-ray diffraction patterns from the inner and outer plate layers were analyzed to discern differences between the layers. Analysis of the X-ray diffraction patterns shows a distinct difference in the relative intensities of the X-ray peaks between the inner and outer layer. These differences are attributable to the iron-sulfur compound, referred to previously.

Resistivity

The resistivities from the inner and outer layers were measured in the laboratory, using a parallel plate arrangement in atmospheric air with relative humidity control. Figure 4 shows the temperature dependence of the resistivities of the inner and outer layers at 8% moisture. The inner layer shows a somewhat higher resistivity, principally at the lower temperature, than the outer layer.

In order to ascertain the extent of electrochemical effects upon flyash, a sample of hopper flyash mixture was maintained in the resistivity apparatus with a potential of 2KV applied at the condition of 700°F and 8% moisture. To discover the effect of temperature only, another hopper flyash sample was maintained at 700°F and 8% moisture. The resistivity for these two samples was obtained over an extended time period. The flyash resistivity measurements from the experiment are presented in the following table:

FLYASH RESISTIVITY

Time (Hrs.)	Heated Sample	Sample Heat Plus Electrical Current
3	1.97×10^9 ohm-cm	2.45×10^9 ohm-cm
6	1.96×10^9 ohm-cm	3.25×10^9 ohm-cm
9	1.96×10^9 ohm-cm	4.2×10^9 ohm-cm
62	1.67×10^{10} ohm-cm	9×10^9 ohm-cm

These resistivity experiments show that the effect of electrical current, in addiiton to heat does not significantly alter the flyash resistivity. This suggests that the ash layer change is thermochemical. It need not be electrochemical reaction.

Power-Off Rapping

The use of power-off rapping was attempted in the field in order to stop the power deterioration. Results of the electrical readings for Plant A, with one side having normal rapping and the other half of the unit employing power-off rapping, are shown in the following table. Results after 8 weeks of operation indicate the improvement was due to power-off rapping technique.

POR Side			Non-POR Side		
TR Set	Secondary KV	Secondary AMP	TR Set	Secondary KV	Secondary AMP
A	20	.86	B	Off	
C	19	.44	D	26	.58
E	POR		F	24	.39
G	21	1.30	K	25	.40
J	21	1.38	H	24	.20
L	33	1.31	M	22	.19

SUMMARY

The load variation performance of hot-side electrostatic precipitators has been found to differ from cold-side electrostatic precipitators.

The governing condition for the proper design of precipitators can be partial boiler load condition, rather than full boiler load condition. The partial load condition can require the precipitator to adequately collect a higher loading of higher resistivity particulates than would be present at the full boiler load condition.

The hot-side precipitator can adequately perform through boiler load variations by the following approach: Precipitator design should reflect the governing condition, as well as use an intelligent rapper system, advanced electronic control system, and power-off rapping with a high degree of sectionalization.

References

1. White, H. J., Electrostatic Precipitation/Fly Ash, Journal of the Air Pollution Control Association, Volume 27, No. 1, January 1977.
2. Lane, W. R., Factors Detrimental to Electrostatic Precipitator Performance ASME '77, WA/APC-7, 1977.
3. Tassicker, O. J., Performance of Cold-Side and Hot-Side Electrostatic Precipitators Treating High Resistivity Fly Ash

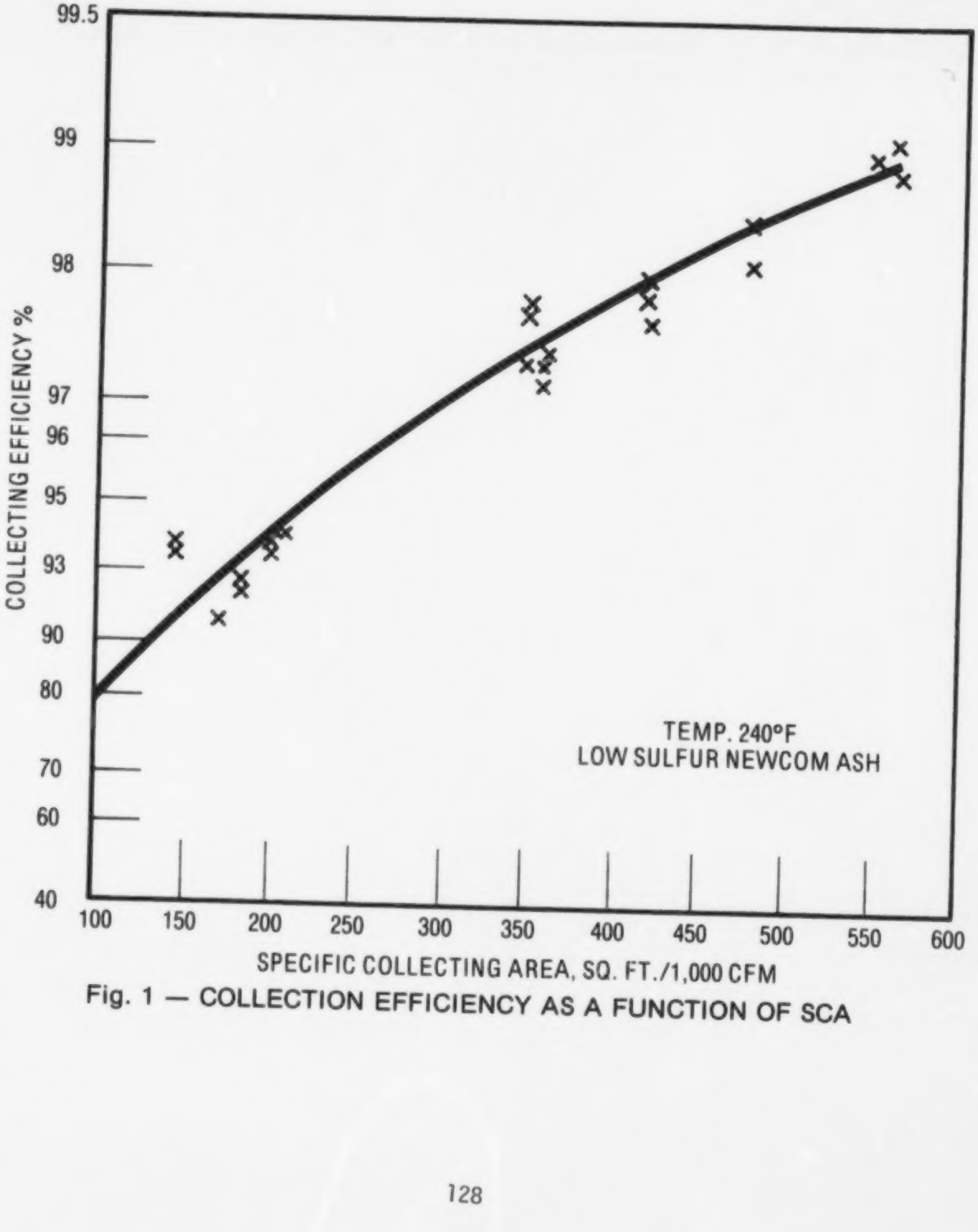

Fig. 1 — COLLECTION EFFICIENCY AS A FUNCTION OF SCA

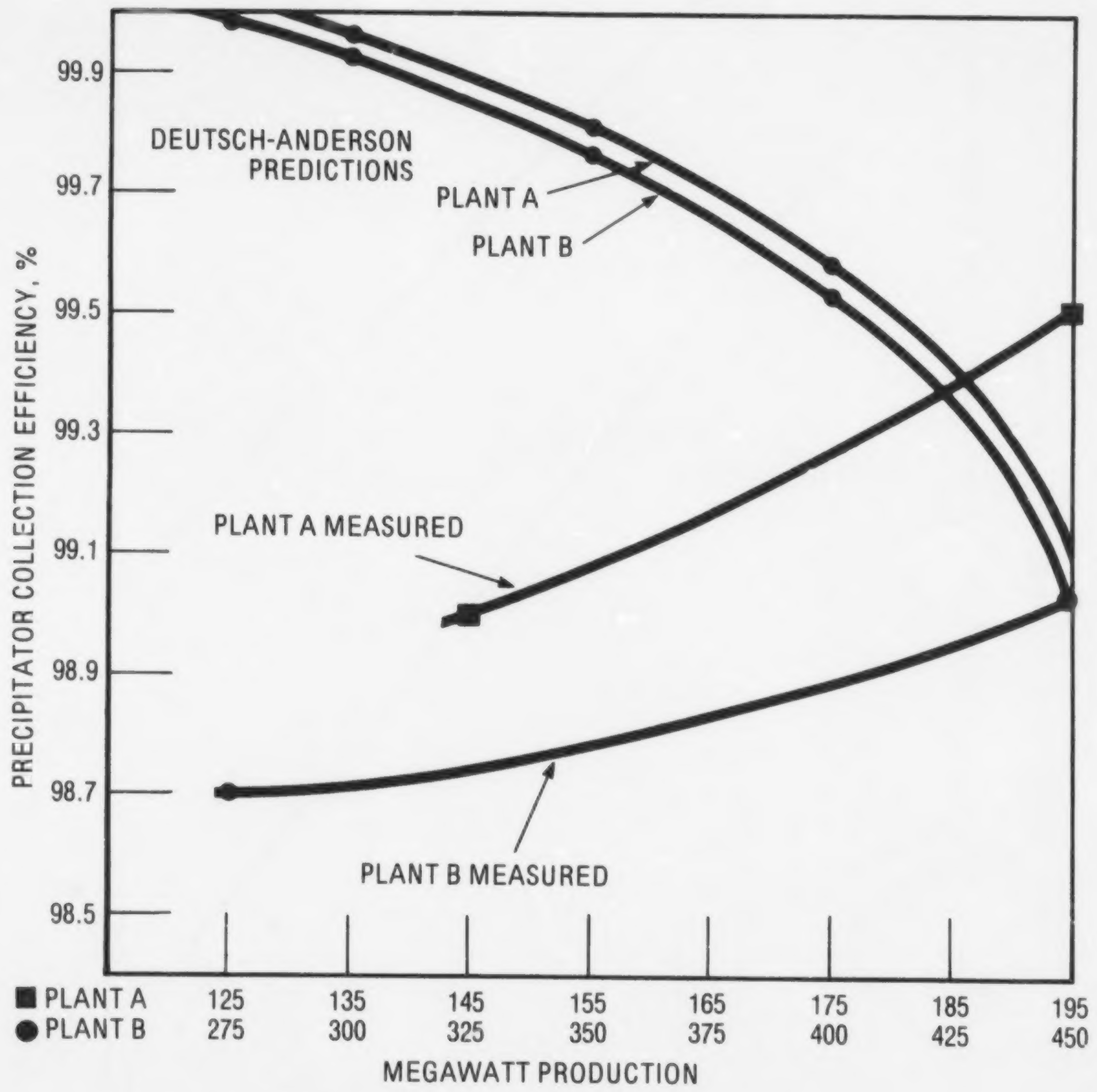

Fig. 2 — HOT SIDE PRECIPITATOR PERFORMANCE WITH LOAD

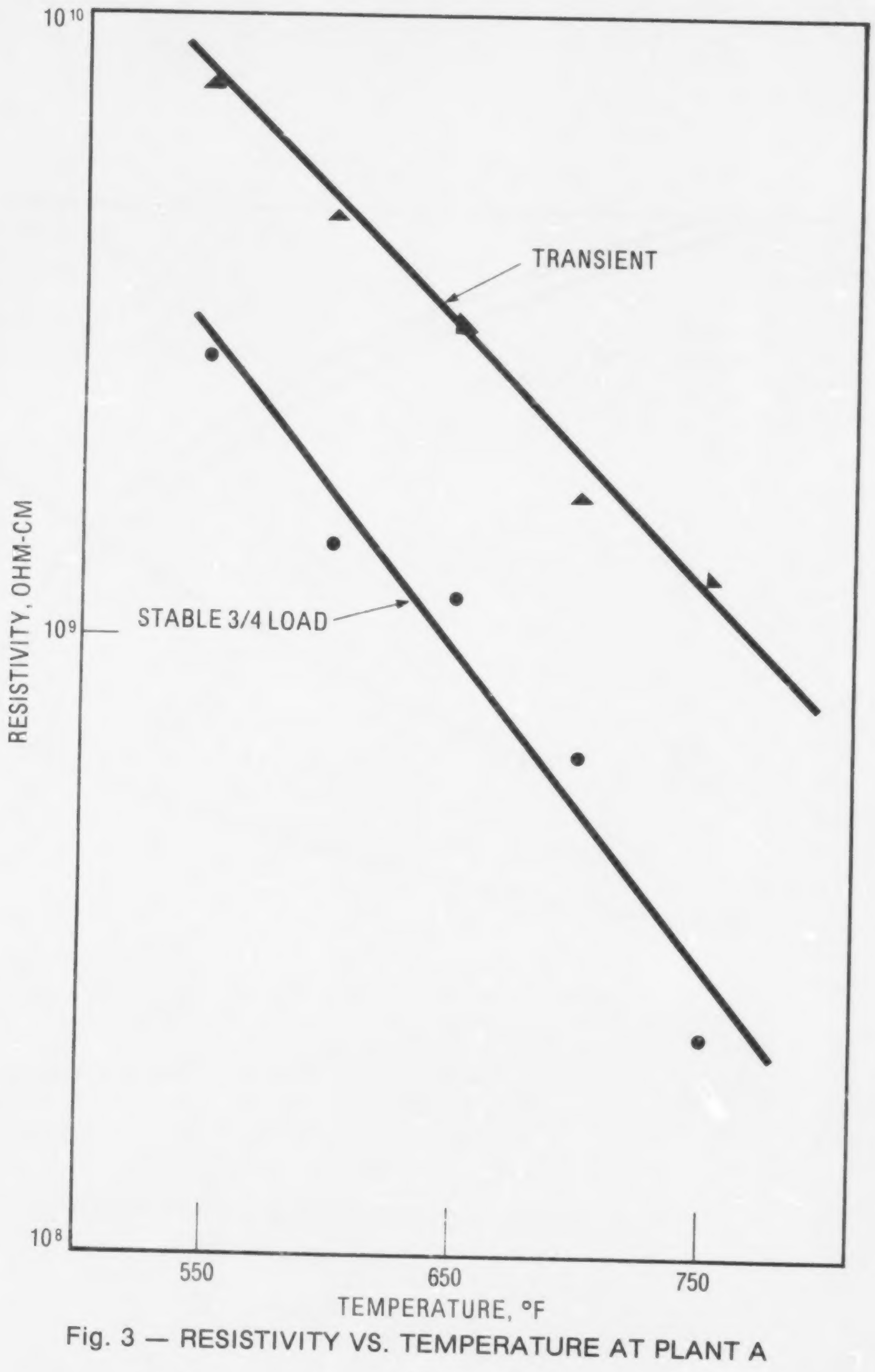

Fig. 3 — RESISTIVITY VS. TEMPERATURE AT PLANT A

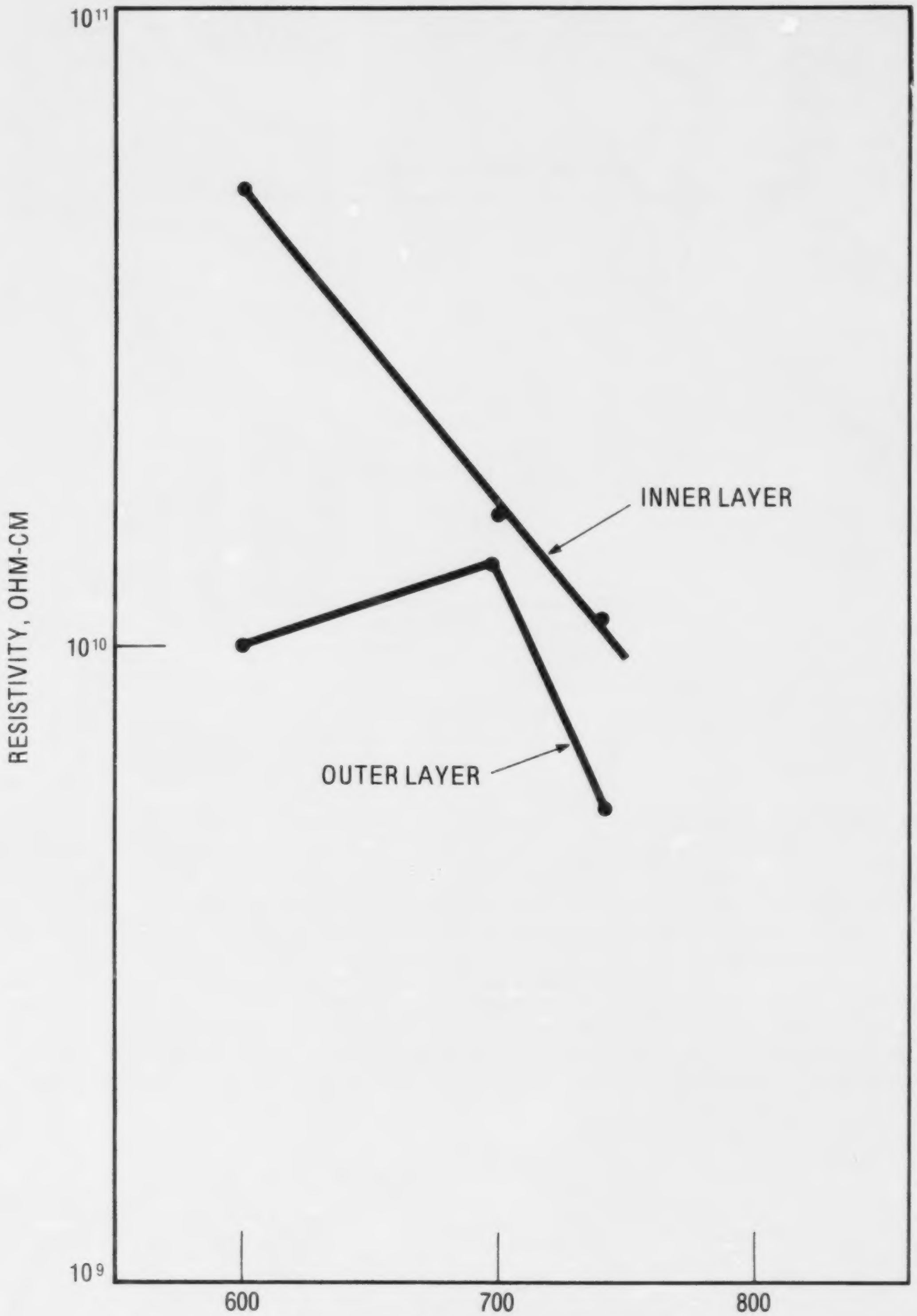

Fig. 4 — RESISTIVITY VS. TEMPERATURE

FLY ASH CONDITIONING BY COPRECIPITATION WITH SODIUM CARBONATE

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ABSTRACT

A temporary solids handling system has been installed at a 55 MW coal-fired utility power boiler to inject sodium carbonate powder into the flue gas stream entering an electrostatic precipitator. The coal used in the boiler produces a high resistivity fly ash under normal operating conditions at 160°C. Field measurements and supporting laboratory studies are underway to evaluate the concept of attenuating resistivity by coprecipitation of sodium carbonate powder with fly ash on the collecting electrodes of the precipitator. This paper gives a progress report on results obtained thus far.

FLY ASH CONDITIONING BY COPRECIPITATION WITH SODIUM CARBONATE

INTRODUCTION

This paper presents the results obtained to date on a field trial of sodium carbonate conditioning of fly ash conducted by Southern Research Institute under contract with the Environmental Protection Agency. The contract includes as major tasks: 1) the selection of a suitable boiler for the use of sodium conditioning in a cold-side precipitator collecting ash from a low-sulfur, low-sodium western coal; 2) the design of a dry, cold-side sodium carbonate injection system; 3) an evaluation of the precipitator performance with and without conditioning; and 4) a comparison of sodium conditioning and sulfur trioxide conditioning.

The project, with the cooperation of the Department of Public Utilities of the City of Colorado Springs, Colorado, involved the Martin Drake Power Station Unit 5 boiler. This installation provided suitable circumstances for the conditioning evaluation, including a sulfur trioxide injection system for the electrostatic precipitator which could be used for direct comparison of the two conditioning processes.

BACKGROUND

In 1971 research involving fly ash resistivity was conducted under the sponsorship of Calgary Power Limited of Calgary, Alberta, Canada. Later this research was formally presented by Bickelhaupt.[1] This work ultimately led to the unequivocal evidence that, in the absence of significant concentrations of sulfuric acid vapor, the conduction process in fly ash is principally controlled by the ionic migration of sodium ions.

As a consequence of this work, an attempt was made to attenuate the resistivity of fly ash on a commercial scale by conditioning with sodium compounds. Laboratory experiments showed that resistivity could be markedly decreased a predictable amount by simply mixing a compound such as sodium carbonate with the fly ash. However, since the time involved required a quick decision, it was suggested that the commercial conditioning experiment should involve adding the sodium compounds to the coal feed. Since Calgary Power normally burns coal that produces ashes containing 2 to 4 percent "sodium oxide," management accepted this suggestion. Three compounds were used as a sodium source. In each case, the in situ resistivity of the ash was reduced from $\sim 1\times10^{12}$ ohm cm to $\sim 1\text{-}5\times10^{10}$ ohm cm when the sodium "oxide" content of the ash was increased to ~2.5 percent from the inherent 0.3 percent. Parts of this research and the results of the sodium conditioning field tests were later recorded by White[2] in a review of resistivity problems.

Subsequently a report by Bickelhaupt[3] was issued outlining the rudimentary principles for conditioning by adding sodium compounds to the coal feed. This technique has not been widely used because of potential slagging, fouling, or corrosion problems related to boiler operation. Southern Research Institute has participated in two additional short-term field studies involving the addition of sodium carbonate to the coal feed. In one case, the results were marginally successful; in the other, they were uninterpretable. (No serious attempt was made to define the reasons for the degree of success.) Considerable effort is sometimes required to determine the reason for an unsuccessful demonstration or execution of a process that is theoretically and technically valid. Recently, the authors have been advised that successful sodium conditioning has been conducted in which sodium carbonate was added to the coal feed.

Unsophisticated laboratory experiments have been conducted to illustrate the effectiveness of ammonium ions and alkali metal ions for increasing the electrical conduction of fly ash. Experiments have also been run to examine the conduction mechanism related to sodium at high and low temperatures. However, no laboratory experiments regarding the techniques or procedures for fly ash conditioning have been conducted by Southern Research Institute.

The first observations of the influence of sodium concentration of fly ash resistivity were made at the Grand Forks, North Dakota, Energy Research Center during studies of fouling potentials for lignites and other western coals. After simple laboratory experiments, more sophisticated evidence was obtained regarding sodium conditioning. The possible use, as conditioning agents, of fly ashes having very large concentrations of sodium and other high sodium ores and minerals was reported by Selle, et al.[4] and Selle and Hess.[5] By reentraining premixed, -100 mesh blends of high resistivity ash and sodium compounds into an environmentally controlled cold-side pilot precipitator, the effectiveness of sodium conditioning was evidenced by increased migration velocity and decreased in situ resistivity. This effect was similar to the coprecipitation of fly ash with sodium compounds formed in situ by reaction between volatilized sodium and other gaseous species. The investigators acknowledged that problems concerning agent delivery and optimum particle size could develop in translating these experiments to a commercial venture. These papers represent the first reported effort to examine sodium conditioning in which the agent was not added to the coal feed.

The first commercial utilization of sodium conditioning on a continuous basis involved a hot-side precipitator.[6] Observing that low-sulfur, low-sodium western ashes can have high resistivity at hot-side temperatures and that dielectric breakdown strength is lower, sodium conditioning was attempted. To avoid the boiler, the sodium compound was added as an aqueous solution atomized into the gas stream between the economizer and the precipitator.

No information was given about the fly ash-sodium compound homogeneity or the concentration of sodium with or without conditioning. However, the reported precipitator efficiency data, the current-voltage relationships, and the *in situ* resistivity data indicate that the conditioning procedure was highly successful.

Schliesser attempted to demonstrate the effectiveness of sodium carbonate as a conditioning agent using a pilot precipitator and the cold-side slipstream from a commercial boiler.[7] This test used a dry injection system that delivered a controlled amount of sodium carbonate powder (8 μm mmd, Bahco) to the slipstream. The fly ash was produced from a low-sodium, low-sulfur western coal.

Although there are certain ambiguities in the results and procedures, the general conclusion was that the conditioning effect was significant. *In situ* resistivity data showed considerable scatter and contained values much too high for the stated concentration of sodium carbonate. Unfortunately sodium concentrations from the resistivity probe samples and pilot precipitator collection plates were not available. In spite of the minor effect on resistivity, efficiency determinations and allowable current density values indicated that a desirable conditioning effect had occurred.

Laboratory, pilot precipitator, and commercial results involving sodium conditioning have recently been reported for hot-side installations by Lederman et al.[8] Laboratory tests utilized a wire-pipe precipitator and reentrained ashes that were coated with conditioning compounds by dry mixing or spraying with solutions. All compounds containing alkali metal ions gave favorable results. Later an aqueous solution of sodium carbonate was sprayed into the duct work prior to extraction of a slipstream to a wire-pipe pilot precipitator. Current-voltage data and efficiency measurements indicated that favorable conditioning had been achieved.

Based on these data, sodium conditioning (sodium carbonate) for hot-side units has been put into commercial service utilizing both aqueous solutions and dry powder injections. Efficiency and current density measurements were given in evidence of their success.

In summary, data have been accumulated showing the technical feasibility of sodium conditioning both in the laboratory and commercially with respect to additions of sodium compounds to the coal feed and either dry or as aqueous solutions preceding a hot-side precipitator. Data from pilot precipitator tests have shown the effectiveness of sodium compounds injected dry as conditioning agents when used in conjunction with cold-side precipitation. From the available information, a commercial evaluation of sodium conditioning by dry injection of sodium carbonate into the gas stream between the air preheater and the precipitator seemed in order.

PLANT AND PROCESS DESCRIPTION

Unit 5 at the Martin Drake Power Plant is owned and operated by the City of Colorado Springs, Colorado. The unit is rated at 44 MW, and includes a Riley Stoker Pulverized Coal Boiler which is a front wall fired, balanced draft furnace. Unit 5 is normally operated at a 54 MW generating rate and fires approximately 22,680 kg (25 tons) of coal per hour. The typical coal burned at Martin Drake is a low-sulfur, low-sodium coal obtained from mines near Craig, Colorado.

The electrostatic precipitator installed on Unit 5 was manufactured by American Standard, Inc., and was designed to operate downstream of a mechanical collector with a collection efficiency of 96.0 percent at a design specific collection area (SCA) of 77.2 $m^2/(m^3/sec)$ (392 $ft^2/1000$ acfm). There are four electrical fields in the direction of gas flow, and each field is powered by one transformer rectifier (TR), which is connected to two electrical bus sections each of which is operated in a half-wave mode. Each field consists of 46 gas passages spaced 22.9 cm (9 in.) apart. The collecting electrodes are 2.29 m (7.5 ft.) deep and 9.14 m (30 ft.) high which results in 1932 m^2 (20,700 ft^2) of collecting surface per field. The discharge electrodes are straight 2.7 mm (0.106 in.) diameter wires spaced 17.8 cm (7 in.) apart in the direction of gas flow. Each field is equipped with 12 electric impulse rappers for the collection electrodes and 4 electric vibrators for the discharge electrodes. A sulfur trioxide injection system enables the precipitator to maintain plume opacity below 20 percent.

The soda ash injection system consisted of a vessel for storing sodium carbonate powder, a flexible screw feeder for unloading barrels of sodium carbonate into the storage hopper, two parallel metering feeders followed by rotary air locks, and two blowers to convey the powder from each feeder into the duct. The conveying lines discharged the sodium carbonate powder onto two dispersion cones to improve the distribution of the powder across the inlet duct. Figure 1 is a schematic side view showing the location of the injection nozzles and dispersion cones in the inlet duct work.

Sodium carbonate powder for the conditioning experiment was obtained from Stauffer Chemical Company from the dust collection system normally used to collect the "fines" which are not suitable for standard applications. Obtaining the proper size distribution of sodium carbonate for the experiments was an important consideration, since the size distribution of the injected powder will influence the uniformity with which the fly ash and conditioning agent are coprecipitated. It was considered impractical to install a pulverizer and the necessary auxiliary equipment for an experimental program, and it was therefore decided to use the powder collected from the dust collection equipment at Stauffer. The variability of the size distribution from the source presented a problem, as illustrated by Figure 2. The material originally supplied from the dust collection equipment gave a reasonable match with the fly ash distribution at the precipitator inlet. However, this parameter was not a controllable variable, and the material later supplied in bulk was deficient in small (<2 μm) diameter particle concentrations. This problem was overcome by blending sodium carbonate collected in the precipitator with that collected in the cyclone from the dust collection system of the sodium carbonate plant. The symbol in Figure 2 indicating "20% fines" means that the mixture consisted of 20 percent by weight of the sodium carbonate with the small size distribution from the precipitator and 80 percent by weight of the coarser material from the cyclone. Note that, below about 8 μm diameter, this mixture compares favorably with material obtained from another sodium carbonate injection system which included a pulverizer and a baghouse to crush and collect the material prior to injection. Because of the indicated deficiency of sodium carbonate particles with sizes of 8 μm and smaller compared to the fly ash, an injection rate was selected which would provide approximately a 5 percent equivalent increment of sodium oxide, approximately twice the intended dosage level. This was done to increase the mass of sodium carbonate that is collected in the outlet fields of the precipitator.

FIELD TEST PROCEDURES AND RESULTS

The field work at the Martin Drake Unit 5 installation included the following major tasks:

(1) a limited performance evaluation of the precipitator with the sulfur trioxide conditioning system in operation;

(2) a detailed performance test of the precipitator with no conditioning of the fly ash;

(3) an evaluation of the performance of the sodium carbonate injection system;

(4) preliminary sodium carbonate conditioning trials with electrodes in a relatively unclean condition; and

(5) a detailed performance test of the precipitator with sodium carbonate injection used as conditioning technique.

The performance tests on the precipitator included size distribution measurements at the precipitator inlet and outlet with impactors, total particle mass concentration and gas flow measurements using EPA Method 17 at the same location, resistivity measurements with an *in situ* point-plane probe at the inlet sampling location, voltage-current measurements on the precipitator power supplies, and collection of coal and fly ash samples for chemical analysis. Appropriate data from the control room instruments were also recorded during the test program, including plume opacity from an in-stack transmissometer. A five-stage series cyclone was employed to collect size-fractionated samples of fly ash at the precipitator inlet for the determination of soluble sodium content.

Preliminary sodium carbonate injection experiments were begun on November 6, 1978 by discontinuing sulfur trioxide injection, starting the sodium carbonate injection, and performing a power-off rapping procedure on fields 1, 2, and 3 of the precipitator. The objective was to remove as much of the residual dust layers from the plates as possible. A similar procedure was carried out during each of the following 24-hour periods, except that the fourth field also received power-off rapping. The precipitator input power decreased, and opacity increased to well above 20 percent. Since the opacity meter and the TR meters suggested that the precipitator performance was limited by dust resistivity, a plant outage was requested for November 11 and 12 to allow samples to be obtained from the precipitator electrodes for chemical analysis. The unit was brought off line on Friday evening, November 10, and a plan was devised for collecting samples and determining the effectiveness of the injection equipment in distributing sodium carbonate throughout the precipitator.

Table 1 gives the soluble sodium oxide concentrations obtained from traverses at the inlet sampling plane with a five-stage cyclone and a mass train with an in-stack filter during the preliminary injection trials. These data indicate that the injection equipment was delivering approximately the intended dosage of sodium carbonate (equivalent to 5 percent sodium oxide), and that the mixture of "coarse" and "fine" soda ash was providing sufficient fine particle concentrations to result in a 1.5 to 3.3 percent sodium oxide concentration increment in the finer size fractions.

After the unit was shut down for the electrode sampling task, samples of fly ash were obtained from the top of every third lane at the inlet and exit of each field. Similarly, samples were obtained approximately 1.5 meters from the bottom of the precipitator plates where access to this region was possible. Selected discharge wires were also chosen for sample procurement. The precipitator was not rapped after the TR sets and the soda ash feeding system was de-energized so that the ash layers on the plates would represent the composition existing during the operation of the unit.

The samples of fly ash obtained from the electrodes were analyzed for soluble sodium content, and the results are displayed in Figures 3 and 4 as the percentage of equivalent sodium oxide. Previous analytical work with this fly ash indicated that an insignificant portion of the naturally occurring sodium in the fly ash is water soluble. Therefore, determination of the water soluble sodium content indicates the amount of sodium contributed by the conditioning system. The data in Figures 3 and 4 indicate that, after 4 days of operation, the conditioning system had distributed the sodium carbonate with reasonable uniformity across the width of the precipitator. The outlet fields contain lower concentrations as would be expected. However, the data from the leading edge of the last field indicates an incremental sodium concentration which, when combined with the naturally occurring sodium, should give a useful resistivity reduction if the sodium compound is properly distributed.

Data from the top of the precipitator plates indicate uniformly low concentrations of soluble sodium. The dust layers in the region near the top were thin (∿ 1 to 2 mm), and it is hypothesized that the dust collection rates in this region are low and that the relatively thinner layers at the top resulted in a higher ratio of residual ash to recently collected ash than is present at lower plate elevations. Since residual unconditioned ash layers on the plates would form a high resistance in series with recently collected ash, an effort was made to obtain layered samples which would provide data on sodium concentration as a function of distance from the plate. These data are displayed in Table 2 and indicate the expected decrease in soluble sodium oxide concentrations with decreasing distance to the plate surface. These data could only be obtained at lower plate elevations due to the previously mentioned thin dust layers near the top of the plates. However, it is apparent from the data obtained on samples from the top elevation that residual dust layers adjacent to the plate will be deficient in added sodium.

The relatively poor precipitator performance experienced during this injection trial was consistent with laboratory data obtained using a series arrangement of high and low resistivity dust. Therefore, it was decided that it would be necessary to wash the precipitator and initiate the sodium carbonate injection simultaneously with the firing of coal in the boiler in order to obtain a proper evaluation of the coprecipitation conditioning method under cold-side precipitator operating conditions.

The precipitator was thoroughly washed during a regularly scheduled outage in April 1979, and the unit was brought on line May 2 with the sodium carbonate injection system in operation. A performance test of the precipitator was conducted during the week of May 14, and the injection trial was continued through May 25, 1979. At full load operation (54 MW), the plume opacity exiting the precipitator varied from 12 to 44 percent during the time that sodium carbonate was injected. Since it was demonstrated that the plume opacity could not be continuously maintained below 20 percent and since the electrical operating parameters did not indicate that effective resistivity attenuation had been accomplished, the field trials were terminated on May 25, 1979. As of this report, data from the test series are still undergoing analysis. However, sufficient information is available to allow conclusions to be drawn regarding the use of the dry powder coprecipitation technique as a means of accomplishing sodium conditioning of fly ash under cold-side operating conditions.

Secondary voltage and current data from the precipitator power supplies for the three performance tests are given in Table 3 and Figure 5. The voltage-current relationships in Figure 5 have been selected from a large number of V-I curves which were obtained on each power supply during each day of the three test series and are representative of electrical conditions existing at the precipitator inlet and outlet during the measurement programs. The sensitivity adjustments on the TR set control panels were adjusted manually by the plant electrician to obtain the maximum voltage possible in the absence of excessive sparking during each test series. It is obvious that, during the sulfur trioxide injection test sequence, the precipitator exhibited more favorable electrical operating conditions than were indicated during the baseline or the sodium carbonate test series. Both the baseline and sodium carbonate test series V-I curves indicate that the operating points are severely limited by dust resistivity. This indication is consistent with resistivity measurements obtained in the field which is discussed below.

The interpretation of field resistivity data was complicated by the variability of the inherent sodium content of the ash. This variability is illustrated in Figure 6 by the sodium oxide concentrations of fly ash collected in the resistivity probe during the sulfur trioxide conditioning test series.

Also shown are sodium oxide concentrations of ashes obtained from the economizer hopper and from filters which collected test samples at the precipitator inlet and the mechanical collector inlet. The following general conclusions could be drawn from the in situ resistivity data obtained during the three test series:

- The sulfur trioxide injection system reduced resistivity from an average of 5×10^{11} to 6×10^{10} ohm cm at ∿153°C during the sulfur trioxide test series. The sulfur trioxide concentration at the precipitator inlet averaged 8 ppm.
- The in situ resistivity of typical Martin Drake ash without conditioning was ∿1×10^{12} ohm cm at ∿160°C.
- The resistivity of fly ash collected in the probe was not effectively reduced by coprecipitation with sodium carbonate, even when the sample on the probe collection plate contained as much as 7.9 percent soluble sodium as sodium oxide. This is illustrated by the data contained in Table 4.

The averaged collection efficiencies of the precipitator during each of the three test series are given in Table 5. It is obvious from these data that the sodium carbonate coprecipitation process was relatively ineffective as a conditioning technique compared to the sulfur trioxide injection. The performance data suggest that the sodium carbonate injection resulted in improvement of the collection efficiency compared to the baseline test series, but the improvement was not sufficient to allow the 20 percent plume opacity limit to be maintained as Figure 7 illustrates. Figure 8 displays the size dependent efficiency data obtained with impactors during the three test series. These data consistently show the same order of performance as the mass train data given in Table 5.

The analysis of the precipitator performance during the three test series is still in progress. Chemical analyses for the sodium carbonate test series are also still in progress, but sufficient work has been completed to indicate that the injection system was delivering the sodium carbonate to the precipitator at a rate no less than the intended dosage increment of 5 percent sodium oxide equivalent. Soluble sodium concentration in fly ash samples obtained from mass train filters which had traversed the inlet sampling location are given in Table 6, along with similar data obtained from precipitator hopper samples. Typical fly ash and coal composition data from the baseline test series are displayed in Tables 7 and 8, respectively.

SUPPORTING LABORATORY STUDIES

In the preceding section the ineffectiveness of sodium conditioning was documented for the process in which the sodium compound is injected as a dry powder into the flue gas between the air preheater and the precipitator inlet. This occurred even though every conceivable precaution was taken to ensure that the conditioning results would not be masked by the condition of the precipitator, inferior conditioning agent injection system, etc.

It has been shown that the injection system delivered the intended concentrations of a dry sodium carbonate powder selected to have a particle size distribution similar to that of the ash to be conditioned. Furthermore, chemical analyses have shown that the injected agent was present in the collected fly ash to a degree that should have registered a significant influence on the precipitation characteristics. The failure to achieve expected results is not uncommon with respect to conditioning agent trials. Usually one does not have the opportunity to determine the reason for a given end result. In this instance, a strong effort was made both in the field and in the laboratory to explain our results.

Resistivity data expressed as a function of sodium concentration[9] show that an inherent fly ash sodium concentration of about 2 to 3 percent expressed as oxide will produce a resistivity of 1 to 5×10^{10} ohm cm at 145°C. Although the inherent sodium "oxide" concentration at Martin Drake was found to be as high as 3.0 percent on occasion, the usual concentration is 0.4 to 0.6 percent. Therefore, the standard laboratory addition for "conditioning" was 3.5 percent sodium carbonate. This addition would yield a combined inherent and added sodium "oxide" concentration of about 2.5 percent.

The Effect of Sodium Carbonate Concentration Added

Several blends of a typical Martin Drake fly ash with various concentrations of sodium carbonate were prepared. A dry sodium carbonate having a Bahco mmd of 8 μm was used. In conducting this type of experiment, one must select a procedure to blend the fly ash and the conditioning agent. The fly ash was placed in a mortar, and the required amount of brilliantly white soda ash was placed on top. The two components were stirred together with a pestle with no intentional grinding until the two colors were not visually discernible. This procedure was used previously at various times and is herein identified as Severity of Mixing No. 2 (SM2).

Using blends of this description, laboratory resistivity determinations were made to illustrate the effect of the amount of sodium carbonate added. The environment for the resistivity test[10] contained no sulfur oxides. The data from three tests are shown in Figure 9 for sodium carbonate additions of 0.0, 3.5, and 30.0 percent by weight to a typical Martin Drake fly ash. The 3.5 percent addition produced the expected attenuation of resistivity. The 30.0 percent addition shows the effect of establishing a continuous matrix of sodium carbonate throughout the resistivity specimen. This resistivity curve is almost identical to the data produced for a resistivity specimen consisting of 100 percent sodium carbonate.

These data point out the severe discrepancy between the laboratory results and the performance of the conditioning agent in the field. In both cases, fly ash has been treated with a concentration of sodium carbonate capable of producing a significant degree of resistivity attenuation; however, this is manifested only in the laboratory test.

The Effect of Fly Ash-Soda Ash Homogeneity

The degree of intimacy or homogeneity between fly ash particles and sodium carbonate particles was considered as a possible explanation for the observed results. Resistivity experiments similar to those described above were conducted to evaluate the effects of the severity of mixing for a given amount of added sodium carbonate, 3.5 percent. In this series of tests sodium carbonate having a Bahco mmd of ∿ 30 μm was used.

In one case a laboratory resistivity cell was loaded by alternately adding fly ash and then sprinkling on a portion of the pre-weighed, required amount of sodium carbonate until a layered mixture filled the cell. This was designated Severity of Mixing No. 1 (SM1). A mixture was also prepared using the previously described procedure SM2. A third blend of fly ash and sodium carbonate was prepared in a manner similar to that described as SM2 except the simple stirring action was replaced by vigorous grinding action. The later blend was labeled Severity of Mixing No. 3 (SM3).

Figure 10 shows the results of these tests. When the soda ash was layered into the fly ash (SM1), only a minor attenuation of resistivity occurred. Mixing procedure SM2 caused a decrease in resistivity equivalent to that which would be anticipated for a comparable change in inherent sodium "oxide" concentration. The most severe mixing (SM3) caused a reduction in resistivity much greater than one would predict based on the effect of inherent sodium concentration.

These data suggest several interesting points. First, it would seem quite possible that the degree of homogeneity between the fly ash and sodium carbonate produced by SM1 is similar to that produced during coprecipitation of the fly ash and the sodium carbonate in the full scale precipitator. If this is true, the ineffectiveness of the conditioning trials can be understood. It is hoped that, in the concluding effort of this program, samples of ash retrieved during conditioning tests will be examined in the laboratory to determine resistivity and degree of homogeneity. The degree of homogeneity could be evaluated by determining the smallest random sample that can be taken from a large sample and still contain the average concentration of sodium oxide. A comparison of this type for field samples and samples prepared in the laboratory should be informative.

The second point of note is with regard to SM2 producing an attenuation of resistivity equal to the amount of decrease one would expect from an equivalent change in inherent sodium concentration. This degree of mixing or homogeneity produces this effect simply by chance. In retrospect, this was an unfortunate occurrence because it equated the effect of added sodium to that of inherent sodium. Intuitively one would expect the added sodium to be more effective on a weight basis.

The third point is that these data suggest that a much lower concentration of sodium is required to attenuate resistivity a specific amount than is predicted from data based on inherent sodium concentrations. The key to the conditioning technique is the efficient transfer of the agent to the fly ash to produce a reasonably homogeneous mixture. This point is emphasized by the data shown in Figure 11. In this series, SM3 was used with an extremely fine sodium carbonate. The combined vigorous grinding and ultra fine soda ash produced a significant attenuation of resistivity with only a 0.5 percent addition of agent.

Laboratory Evaluation of Series and Parallel Circuits Created from Unconditioned and Conditioned Ash

In the discussion of field test results, it was pointed out that the effect of a solid conditioning agent used to attenuate resistivity would be negated if a layer of unconditioned ash prevailed on the collection plates. This apparently obvious statement was demonstrated with a laboratory experiment.

A quantity of conditioned ash was prepared using 3.5 percent sodium carbonate blended with a typical Martin Drake fly ash employing SM2. Using a 5 mm deep, ASME, PTC-28 resistivity cell, a test specimen was prepared by filling the cup with 2.5 mm of unconditioned ash topped by 2.5 mm of conditioned ash to illustrate the series effect. Another cell was prepared so that 50 percent of the current measuring electrode area superimposed a 5 mm deep layer of conditioned ash while the other 50 percent of the electrode covered a 5 mm deep layer of unconditioned ash to develop a parallel circuit.

The results of these experiments are shown in Figure 12. As anticipated, overlaying a layer of high resistivity dust with a properly conditioned layer of dust has little effect. The result is essentially equivalent to halving the thickness of the high resistivity layer. The parallel circuit experiment demonstrates that if a significant collection plate area is clear of high resistivity ash, a homogeneously conditioned ash will show an improved precipitator performance.

CONCLUSIONS AND RECOMMENDATIONS

- This research indicates that conditioning to attenuate resistivity for cold-side precipitation using a process involving the coprecipitation of fly ash and an injected dry powder can be ineffective. In the specific case, anhydrous, 30 μm mmd, sodium carbonate was injected at ∿ 150°C.
- The above conclusion is opposed to the results mentioned in the background section with respect to similar experiments utilizing a pilot precipitator and a commercial flue gas slipstream.
- In no way do these results imply that sodium conditioning is ineffective when the additive is injected either as a fine dry powder or in an aqueous solution to either the coal feed or the flue gas stream at a temperature equal to or exceeding hot-side operation.
- This research emphasizes the need for caution when quantitatively interpreting the results of laboratory

tests including pilot precipitators that demonstrate conditioning effects using premixed fly ash/conditioning agent blends.

- Assuming a high degree of homogeneity between fly ash and sodium additive, the sodium addition required for a given resistivity attenuation is apparently less than would be predicted from resistivity/sodium concentration relationships based on inherent sodium.

- Methods of achieving the required degree of homogeneity for sodium conditioning with practical injection methods should be explored.

ACKNOWLEDGMENTS

The cooperation and assistance of Ronald L. Ostop, Senior Environmental Engineer of the Department of Public Utilities of the City of Colorado Springs, is greatly appreciated. The assistance of plant personnel at the Martin Drake Power Station is also greatly appreciated.

REFERENCES

1. Bickelhaupt, R. E. Electrical Volume Conduction in Fly Ash. APCA Journal. 24 (3) 251-255. March 1974.

2. White, H. J. Resistivity Problems in Electrostatic Precipitation. APCA Journal. 24 (4) 314-338. Aprii 1974.

3. Bickelhaupt, R. E. Sodium Conditioning to Reduce Fly Ash Resistivity. EPA-650/2-74-092, NTIS No. PB236-922. U. S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711. October 1974.

4. Selle, S. J., L. L. Hess, and E. A. Sondreal. Western Fly Ash Composition as an Indicator of Resistivity and Pilot ESP Removal Efficiency. Paper 75-02.5 presented at: 68th Annual Meeting of the Air Pollution Control Association, Boston, Massachusetts. 1975.

5. Selle, S. J., and L. L. Hess. Factors Affecting ESP Performance on Western Coals and Experience with North Dakota Lignites. In: Symposium on Particulate Control in Energy Processes. EPA-600/7-76-010, NTIS No. PB260-499, 1976. p. 105-125.

6. Walker, A. B. Operating Experience with Hot Precipitators on Western Low Sulfur Coals. Presented at: American Power Conference, April 18-20, 1977. Palmer House, Chicago, Illinois.

7. Schliesser, S. P. Sodium Conditioning Test with EPA Mobile ESP. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Volume 1. Electrostatic Precipitators. EPA-600/7-79-044a, NTIS No. PB295-226, 1979. p. 205-240.

8. Lederman, P. B., P. B. Bibbo, and J. Bush. Chemical Conditioning of Fly Ash for Hot Side Precipitation. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Volume 1. Electrostatic Precipitators. EPA-600/7-79-044a, NTIS No. PB295-226, 1979. p. 79-98.

9. Bickelhaupt, R. E. A Technique for Predicting Fly Ash Resistivity. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Volume 1. Electrostatic Precipitators. EPA-600/7-79-044a, NTIS No. PB295-226, 1979. p. 395-407.

10. Bickelhaupt, R. E. Measurement of Fly Ash Resistivity Using Simulated Flue Gas Environments. EPA-600/7-78-035, NTIS No. PB278-758. U. S. Environmental Protection Agency, Research Triangle Park, North Carolina 27711. 1978.

Table 1. Soluble Na from Na_2CO_3 test series.

DATE	SOURCE		SOLUBLE Na as Na_2O, %
5/19/79	MASS TRAIN FILTER		6.0
5/19/79	MASS TRAIN FILTER		6.6
5/21/79	MASS TRAIN FILTER		11.3
5/22/79	MASS TRAIN FILTER		7.5
5/24/79	MASS TRAIN FILTER		6.2
5/25/79	MASS TRAIN FILTER		5.1
5/19/79	HOPPER, ROW 3	FIELD 1	9.0
		FIELD 2	12.2
		FIELD 3	2.5
		FIELD 4	2.4

Table 2. Na_2O contents in layered samples.

	% Na_2O						
	LANE 16, BOTTOM				LANE 4, BOTTOM		
LOCATION	PLATE	MIDDLE	OUTER		PLATE	MIDDLE	OUTER
FIELD 1, NORTH SIDE, BACK PLANE	1.5	2.1	4.6	← Soluble →	2.4	2.6	5.1
	2.0	2.5	4.7	← Total →	2.9	2.9	5.3
	LANE 19, BOTTOM				LANE 4, BOTTOM		
FIELD 2, NORTH SIDE, FRONT PLANE	0.99	2.4	3.2	← Soluble →	2.8	4.0	4.1
	1.3	2.8	4.3	← Total →	3.2	4.6	4.4

Table 3. Average operating points for TR sets.

TEST NO	CONDITION	DATES	VOLTAGE, kV	CURRENT DENSITY nA/cm^2
1	SO_3 INJECTION	4/25-29/79	34.0	16.7
2	BASELINE	10/10 - 14/78	28.4	8.2
3	Na_2CO_3 INJECTION	5/15 – 19/79	27.5	4.7

Table 4. Resistivity probe data.

SAMPLE DESCRIPTION						
DATE	RUN NO.	LOCATION	SOLUBLE Na as Na_2O, %	TEMP °C	RESISTIVITY ohm-cm	BREAKDOWN kV/cm
5/16/79	5	PROBE TOTAL CATCH	4.8	175	3.7 x 10^{12}	20
5/16/79	8	PROBE GUARD RING	4.5	177		
5/16/79	8	PROBE COLL. PLATE	1.1	177	2.5 x 10^{12}	25
5/18/79	15	PROBE GUARD RING	17.7	160		
5/18/79	15	PROBE COLL. PLATE	7.9	160	6.7 x 10^{11}	46

Table 5. Averaged precipitator performance comparison.

DATE	CONDITION	INLET GAS FLOW DNCM/sec	MASS CONCENTRATION mg/DNCM		PENETRATION %	OPACITY %
			INLET	OUTLET		
4/28-4/29/78	SO_3 INJECTION	62.2	2385	21.6	0.91	7.5
10/13-10/14/78	BASELINE	56.7	2229	27.8	12.5	31
5/18-5/25/79	Na_2CO_3 INJECTION	57.2	2525	16.3	6.46	24

Table 6. Soluble Na_2O contents.

DATE	RUN	D_{50} µm	Na_2O %
11/7/78	MDI-CY10	6.79	15.2
		3.45	6.6
		1.99	3.3
		1.09	3.3
		0.58	2.0
11/8/78	MDI-CY11	5.51	12.1
		2.81	4.8
		1.62	2.0
		0.83	1.7
		0.45	1.5
11/8/78 - Mass train sample from inlet			5.3
11/10/78 - Mass train sample from inlet			6.2

Table 7. Fly ash composition - baseline test series.

Date	Field	Row	Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	Soluble SO_4	LOI
10/10/78	1	3	0.02	1.0	1.1	1.4	4.9	5.0	27.1	55.7	1.0	1.5	0.3	0.5	4.1
	2			1.2											4.5
	3			1.1											3.0
	4			0.9											3.0
10/11/78	1	2	0.02	1.3	1.0	1.6	5.8	5.5	26.6	52.8	1.1	1.5	0.3	0.6	5.2
	2			1.2											3.5
	3			1.4											2.7
	4			1.2											2.7
10/12/78	1	3	0.02	0.5	0.9	2.2	7.1	4.3	29.5	51.8	1.0	1.4	0.4	0.6	3.8
	2			0.6											4.3
	3			0.9											3.5
	4			1.0											4.5
10/13/78	1	3	0.02	0.5	1.5	1.6	4.8	4.6	25.6	57.6	1.0	0.9	0.3	0.5	3.6
	2			0.5											3.8
	3			0.5											3.6
	4			0.8											3.3
10/14/78	1	3	0.02	1.9	1.1	1.7	5.8	4.8	25.3	56.2	1.1	1.0	0.5	0.6	1.9
	2			1.7											1.7
	3			1.0											3.5
	4			1.1											2.5

Table 8. Coal analyses from baseline test.

Date	10/10/78	10/10/78	10/11/78	10/11/78	10/12/78	10/12/78	10/13/78	10/13/78	10/14/78	10/14/78
Time	10:00 AM	3:45 PM	10:00 AM	4:00 PM	11:00 AM	3:00 PM	10:40 AM	3:30 PM	10:50 AM	1:10 PM
As-Received Proximate, Wt.%										
Moisture	11.07	12.63	12.06	16.47	14.34	15.76	14.01	13.69	13.77	13.78
Volatile Matter	35.91	37.45	38.19	35.82	34.66	32.71	35.87	36.02	36.26	36.10
Fixed Carbon	42.71	42.02	42.15	39.11	39.99	37.48	39.67	44.04	44.31	39.17
Ash	10.31	7.90	7.60	8.60	11.01	14.05	10.45	6.25	5.66	10.95
Sulfur	0.63	0.59	0.52	0.50	0.50	0.55	0.55	0.44	0.43	0.47
As-Received Ultimate, Wt.%										
Carbon	61.36	61.83	62.91	57.08	58.18	53.04	58.17	62.27	62.61	58.36
Hydrogen	4.07	4.12	4.06	3.79	3.67	3.38	3.49	4.24	4.40	3.65
Oxygen	11.15	11.76	11.55	12.29	11.00	12.01	11.94	11.78	11.85	11.57
Nitrogen	1.34	1.14	1.25	1.22	1.25	1.15	1.37	1.20	1.22	1.17
Sulfur	0.63	0.59	0.52	0.50	0.50	0.55	0.55	0.44	0.43	0.47
Moisture	11.07	12.63	12.06	16.47	14.34	15.76	14.01	13.69	13.77	13.78
Ash	10.31	7.90	7.60	8.60	11.01	14.05	10.45	6.25	5.66	10.95

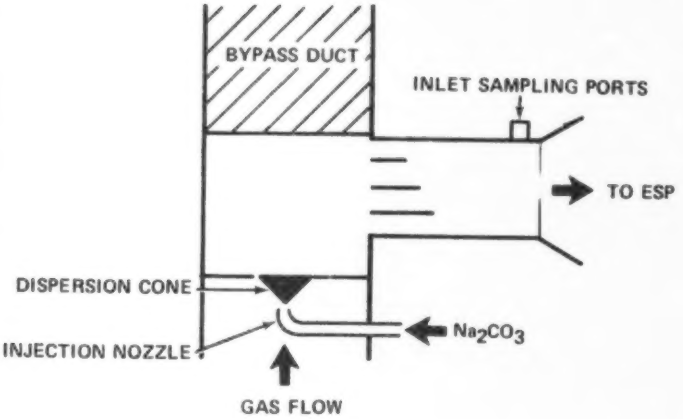

Figure 1. Schematic elevation view of sodium carbonate injection system.

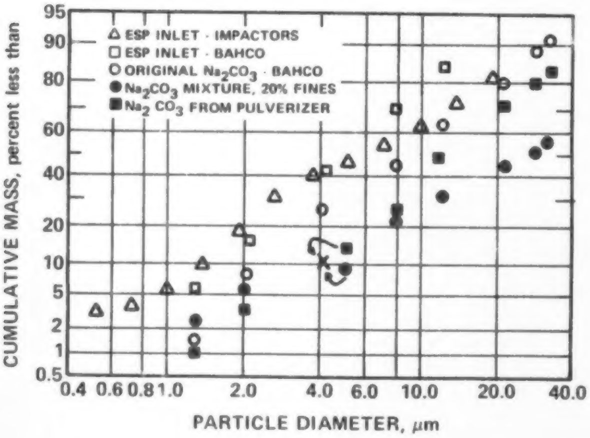

Figure 2. Particle size distributions of Martin Drake fly ash and sodium carbonate.

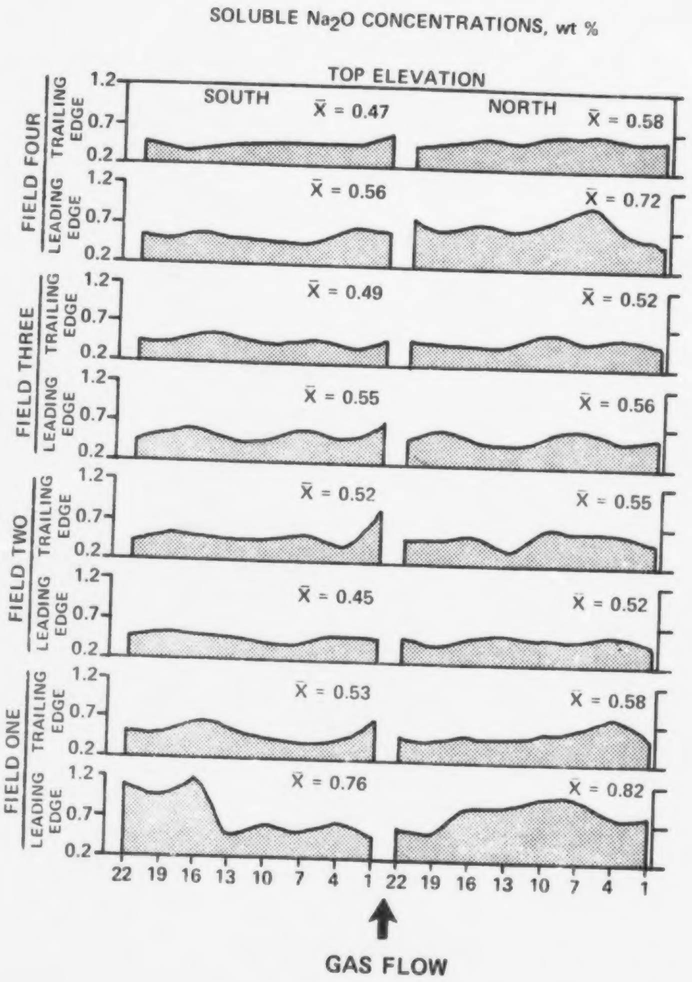

Figure 3. Distribution of sodium after 4 days of injection, top of precipitator.

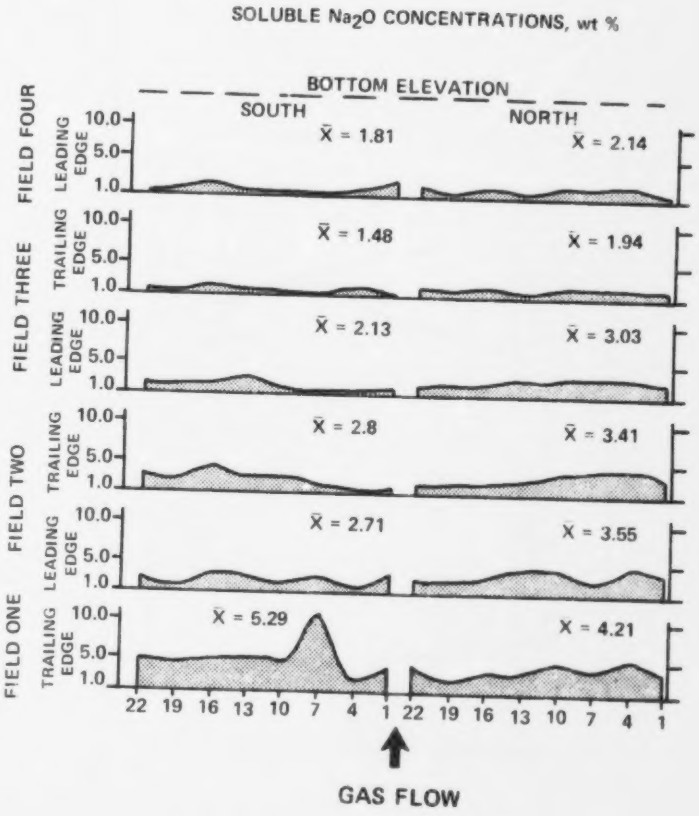

Figure 4. Distribution of sodium after 4 days of injection, bottom of precipitator.

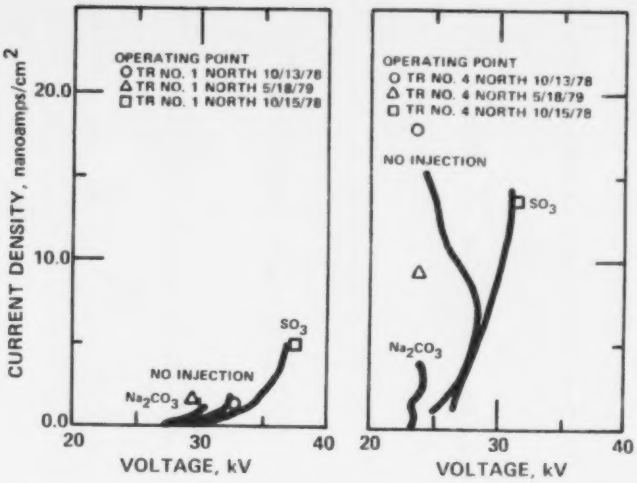

Figure 5. Secondary voltage-current data for three performance tests.

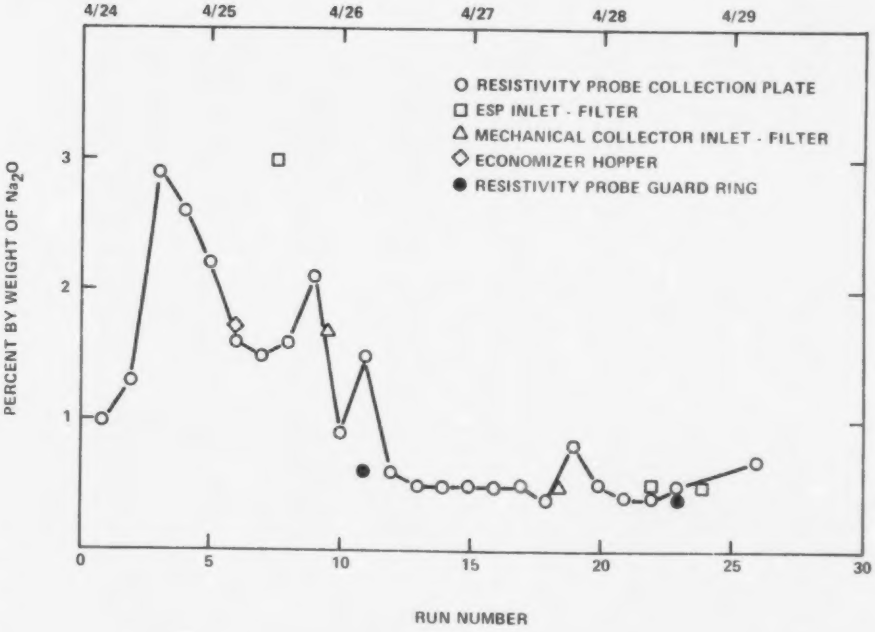

Figure 6. Sodium oxide content of ash samples versus time.

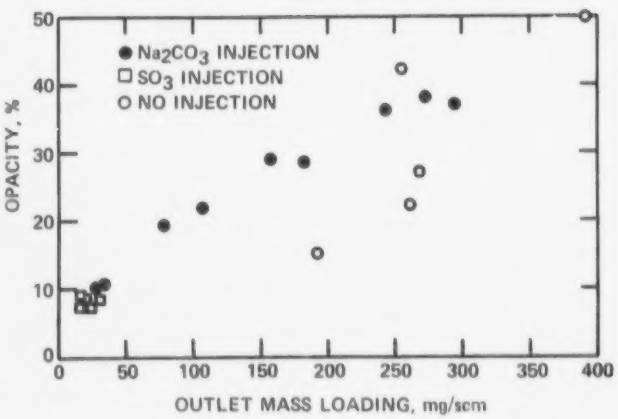

Figure 7. Opacity versus outlet mass loading.

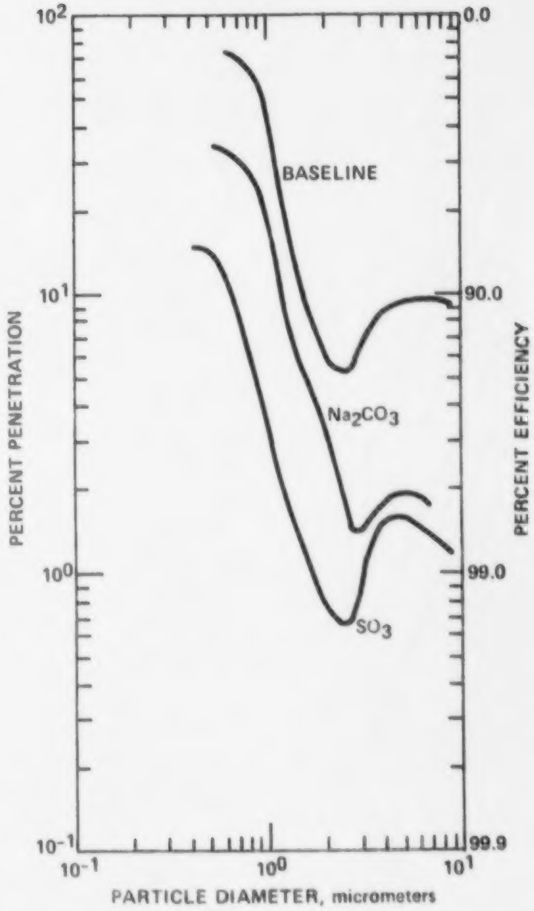

Figure 8. Fractional efficiency for three performance tests.

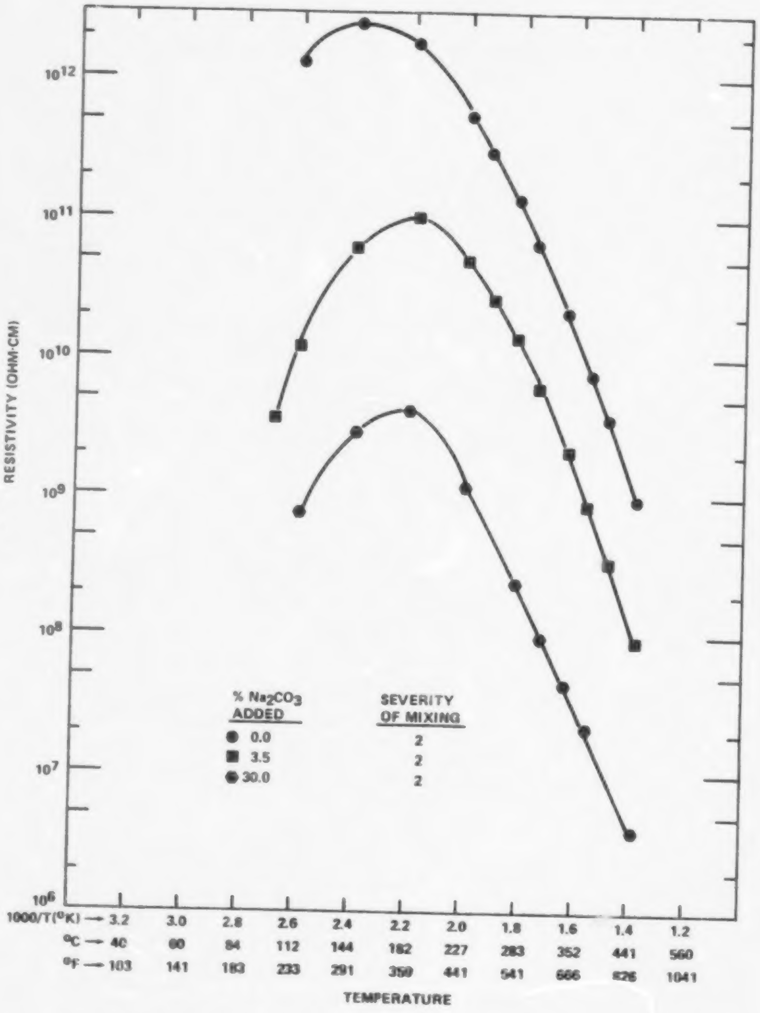

Figure 9. Effect of the amount of sodium carbonate added on the resistivity of a fly ash.

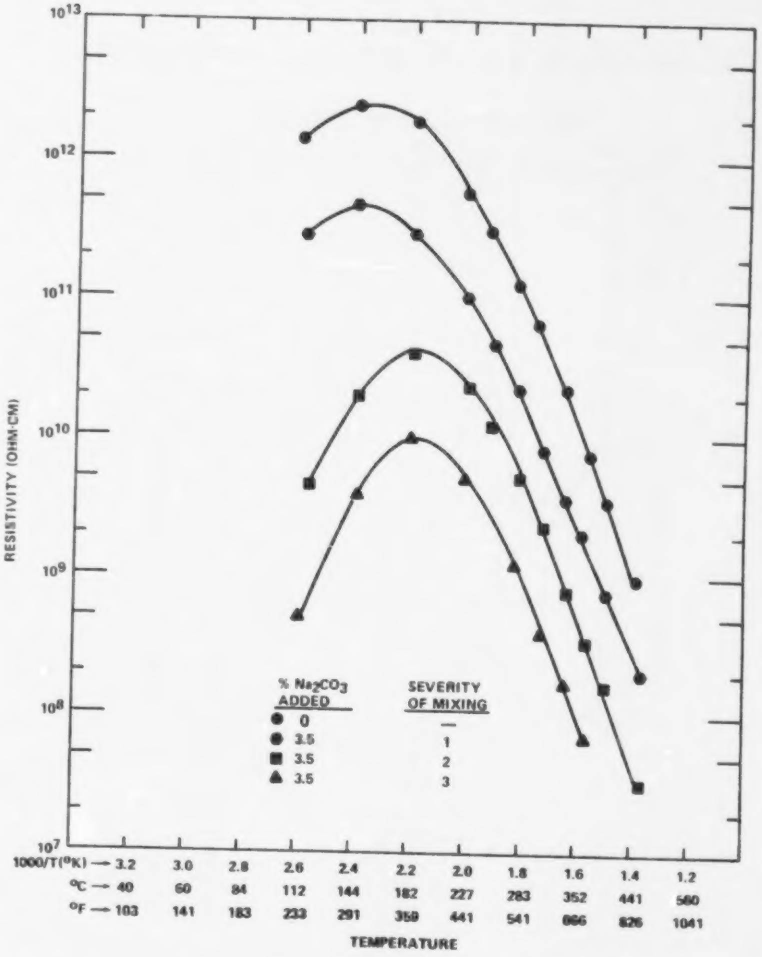

Figure 10. Effect of the intensity of mixing fly ash and a given concentration of sodium carbonate on resistivity.

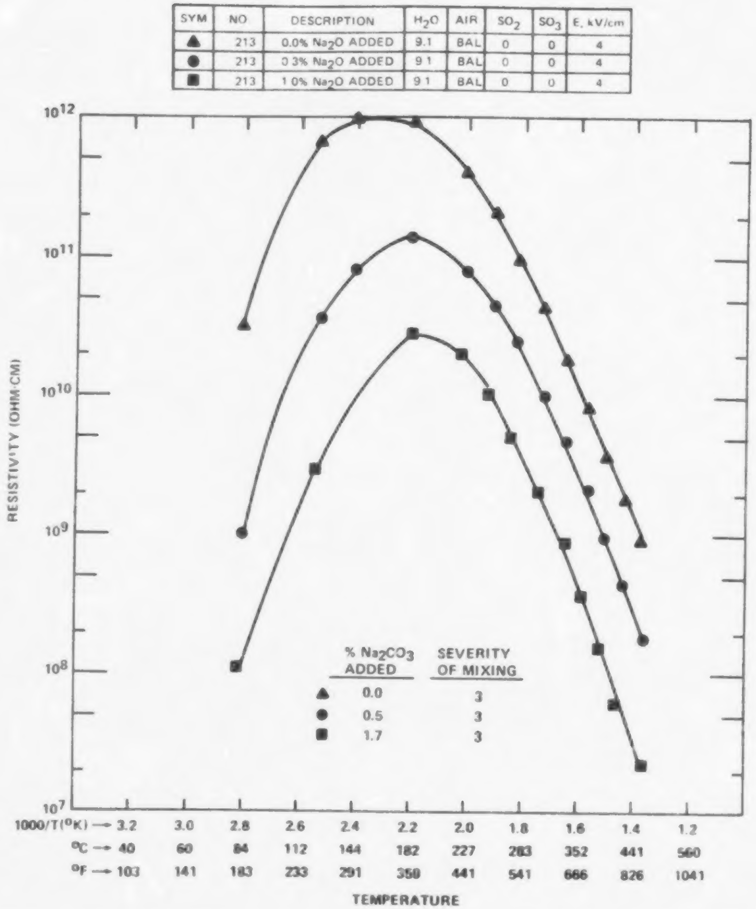

Figure 11. *Effect of sodium carbonate particle size and intensity of mixing on the resistivity of a fly ash.*

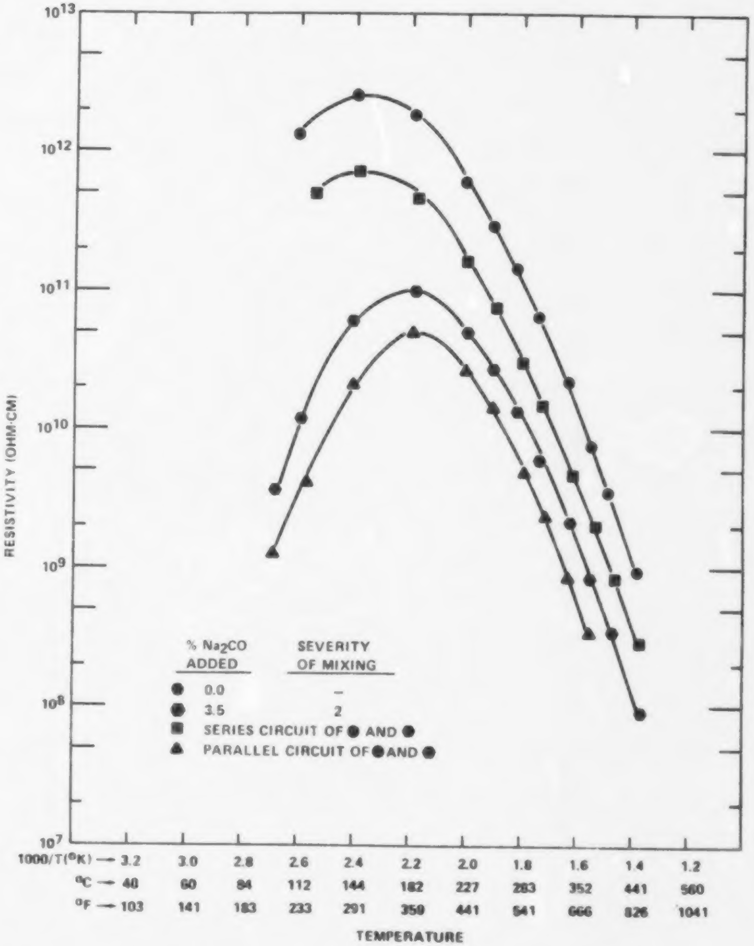

Figure 12. *Effect on resistivity of unconditioned and sodium-conditioned ash forming series and parallel circuits.*

PREDICTING FLY ASH RESISTIVITY - AN EVALUATION

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ABSTRACT

Recently a technique for predicting fly ash resistivity from an as-received, ultimate coal analysis and the chemical composition of the coal ash produced by simple laboratory ignition was published. This paper evaluates this technique by comparing predicted resistivity data with laboratory measured values, in situ resistivity data, and precipitator performance information acquired from 12 field test programs. Considering the precision of measurement generally encountered in precipitator technology and the limited amount of certain laboratory data available, the results are encouraging and the evaluation is favorable.

PREDICTING FLY ASH RESISTIVITY - AN EVALUATION

INTRODUCTION

Electrical resistivity is an important property in the design of an electrostatic precipitator for the dry collection of fly ash. For a given collection efficiency, high resistivity necessitates large precipitators requiring greater capital investment and operating expense. Although resistivity data serve many purposes, the principal use of these data is for sizing precipitators with respect to design coals.

If the given design coal is relatively uniform in character and the precipitator manufacturer has had experience with the coal, the design problem is minimal. This desirable situation is not available in many instances. However, there are several ways in which the required resistivity data can be obtained. In situ resistivity measurements can be made if the coal is being commercially burned. When the design coal is not being burned in a full scale boiler, small samples of the coal can be fired in laboratory scale boilers to produce a fly ash. The resistivity of ash produced in this manner can be measured in situ or after removal from the flue system. A third alternative is to predict the resistivity of the fly ash using the chemical compositions of the ash and the flue gas.

The subject of this paper is an evaluation of a method for predicting fly ash resistivity. Predicted resistivity values are compared with resistivity data acquired in situ and in the laboratory. To help interpret the quality of the predicted data, precipitator efficiency and outlet-field current density values are also considered.

BACKGROUND

Recently a technique for predicting resistivity has been published.[1] The predictive technique is dependent on a series of correlations between laboratory-measured resistivity and the factors that influence this property. Factors included are fly ash composition, flue gas analysis, and the field strength in the ash layer. A large number of fly ash specimens were used to develop the correlations with the intention of minimizing the effect of ash layer porosity and specific surface. Utilizing the chemical composition of a coal ash and the flue gas composition calculated from the stoichiometric combustion of the coal, the correlations are used to predict fly ash resistivity. The method is applicable to the most fundamental case; that is, the prediction of fly ash resistivity from a core bore sample of coal.

Obviously the quality of the predicted resistivity data depends on: 1) the relatively good agreement between the true value of resistivity and the value determined in the laboratory, 2) the ability to produce coal ash having a chemical composition similar to fly ash, and 3) the ability to predict the flue gas analysis, in particular the amount of sulfur trioxide. This paper attempts to assess the quality of the resistivity predictions.

Table 1 illustrates the printout of data from the computer program based on the subject predictive technique. The first page of the table shows the input of the as-received, ultimate coal analysis from which the stoichiometrically calculated flue gas composition is acquired using 30 percent excess air. The data critical to the calculation of resistivity are gathered at the bottom of the page: water concentration in volume percent, sulfur trioxide in ppm on a dry volume basis, and ash layer field strength, E. The field strength unless otherwise noted is always taken as 10 kV/cm. The value of sulfur trioxide is computed as 0.4 percent of the stoichiometrically calculated sulfur dioxide value. On the second page of Table 1, the chemical composition of the coal ash is the input data. The technique for producing the coal ash is shown at the bottom of the page. Chemical elements of importance to the prediction of resistivity are shown immediately below the ash composition. The output data are resistivity values as a function of temperature. The columns headed RHO (VS) and RHO (VSA) are the predicted resistivity values without and with the effect of sulfuric acid vapor taken into account respectively.

Figure 1 shows this type of data plotted as a function of reciprocal absolute temperature. The pronounced influence on resistivity of sulfuric acid vapor in the flue gas is shown. *In situ* and laboratory measured resistivity data are superimposed on the curve of predicted data. Table 1 and Figure 1 illustrate the source of the data used in the evaluation that follows.

EVALUATION OF THE TECHNIQUE FOR PREDICTING RESISTIVITY

Concurrently with the research effort to produce the resistivity predictive technique, field tests[2,3] were conducted to evaluate various aspects of precipitator performance and operation. While power stations were operating under normal full-load conditions, the following data and samples were obtained within the shortest possible time: isokinetic fly ash sample, representative coal sample, *in situ* resistivity data, flue gas analysis, outlet-field current density-voltage relationship, and mass train efficiency measurement.

The coal samples were ashed according to the method defined in Table 1, and the resulting chemical analysis was compared with the concomitant fly ash analysis. The coal ash chemical analysis also served as input data for the resistivity prediction.

The fly ash samples were chemically analyzed and used for laboratory resistivity determinations. When resistivity was determined using these specimens, the environment was air containing the water and sulfur trioxide concentrations reported for the field test flue gas. The temperature used was the same as that recorded during the in situ resistivity measurement. The last current reading prior to dielectric breakdown was used to calculate laboratory resistivity.

The data and samples from tests at 12 power stations are used in this evaluation. Table 2 presents general information about the stations involved and the analysis of the coal being burned during the field test period. The ultimate coal analyses shown were used to determine the predicted flue gas analyses. These predicted values were compared with the measured flue gas analyses and were used in the resistivity prediction. The W or E following the power station number indicates that coal from the western or eastern part of the country was being burned.

Coal Ash - Fly Ash Comparison

Table 3 shows the comparison of fly ash and coal ash chemical compositions and the comparison of in situ and predicted flue gas analyses. The subject technique for predicting resistivity utilizes the concentrations in atomic percent of lithium plus sodium, magnesium plus calcium, and iron. The only obvious difference between the fly ash and coal ash analyses with respect to the elements of interest concerned the iron concentration for stations 3 and 5. These deviations would only affect high temperature resistivity. At 350°C, predicted resistivity based on the coal ash analysis was nearly a factor of two greater than the predicted value using the fly ash analysis.

In Situ - Predicted Flue Gas Comparison

Considering the comparison of in situ and predicted flue gas analyses, the water concentration and sulfur trioxide concentration are most important. The largest deviation between in situ (8.1%) and predicted (10.5%) water concentrations occurred at station 5. In this case under typical cold-side precipitator conditions, the predicted resistivity would be about a factor of 1.5 lower than a predicted value based on the in situ water concentration. In general, the predicted and in situ water concentrations showed excellent agreement. The average values for the predicted and measured water concentrations for the 12 stations were identical. Six times the predicted value was greater than and six times it was less than the respective measured value.

The comparison between the predicted values for the sulfur trioxide concentration and values measured in situ is more difficult to assess. It was mentioned above that the predicted sulfur trioxide value was obtained by multiplying the sulfur dioxide value calculated from the stoichiometric combustion of the coal by 4×10^{-3}. This multiplier was selected after reviewing the information from 17 field test programs conducted by Southern Research Institute prior to this paper. In this method of predicting resistivity, it is assumed that at the precipitator inlet the fly ash is in equilibrium with the sulfur trioxide concentration measured in situ and that in the laboratory the volume of fly ash under test is in equilibrium with this same concentration of sulfur trioxide at the time that the resistivity data are taken.

For five of the six stations burning eastern coal and having an in situ sulfur trioxide concentration greater than 1 ppm, a range of values is given. In each case, the predicted value for sulfur trioxide was within the range established by in situ measurement. Only in the case of station 12, burning a coal of very low sulfur content, was the predicted value significantly different from the in situ value. Awareness of the problems encountered in making in situ sulfur trioxide determinations leads one to speculate that this value could very well have been greater than the recorded 0.5 ppm.

The average sulfur concentration for the six stations burning western coal was 0.5 percent, and the predicted average sulfur trioxide concentration was approximately 2 ppm. In all cases, the measured concentration was < 1 ppm. A possible explanation for this difference is related to the difficulty in making precise in situ sulfur trioxide determinations especially at very low concentrations combined with the greater affinity of the more alkaline western ash for the sulfuric acid vapor. Although this deviation is small, it can have a significant effect because the sulfuric acid vapor has a very pronounced effect on resistivity.

Comparison of Predicted, Laboratory, and In Situ Resistivities

Before comparing the predicted resistivity values with measured resistivity data and precipitator performance information, several important points should be noted. First, the predicted resistivity is based on the water and sulfur trioxide concentrations calculated from the stoichiometric combustion of the coal, while the laboratory measurement of resistivity was conducted in an environment in which an attempt was made to duplicate the in situ concentrations of these agents. When the in situ value for sulfur trioxide was < 1 ppm, the laboratory environment contained approximately 1 ppm. Because of the inability to precisely duplicate environments, it is noted that small differences existed in the environments used for predicted, in situ, and laboratory-measured resistivities. Second, one should recall that resistivity determinations are not extremely precise. Although no statistical interpretation is available, repetitive laboratory determinations of identical specimens will yield an average value with a data spread of ±30 percent. The in situ data are usually averages for several determinations made during the test period of interest. Although atypical, the range of in situ values for a series of determinations can cover an order of magnitude.

To avoid repetitive explanation for certain observations, the data shown in Table 4 are best discussed in three groups: data pertaining to hot-side precipitators, cold-side precipitators burning western coal, and cold-side precipitators burning eastern coal.

The field test data were available for hot-side precipitators from two power stations, 4E and 6W-13W. The data for stations labeled 6W and 13W represent two sets of data from the same installation. For each of three sets of data, the laboratory-measured resistivity value was in good agreement with the predicted value. In one instance, station 13W, the in situ resistivity measurement was identical to the value obtained in the laboratory, while at the other, station 4E, the in situ value was one order of magnitude greater than the predicted and laboratory-measured values. It should be noted that only one resistivity data point was obtained at station 4E before the high-temperature resistivity probe degraded due to mechanical and thermal abuse. The precipitator performance data for station 4E cannot suggest which resistivity data are more likely to be correct. The low current density and the evidence of back-corona for the 13W and 6W stations, respectively, were judged not related to the inherent resistivity of the fly ash.

Data are available from four stations burning western coal and operating cold-side precipitators. These stations are designated: 1W, 5W, 10W, and 11W. Laboratory-measured resistivity data were greater than the respective predicted data by a factor of 2 to 4. Since in each case the water and sulfur trioxide concentrations used in the resistivity prediction were slightly greater than the concentrations used in the laboratory test environment, the agreement between laboratory results and predicted data is outstanding. However, only the in situ data for station 1W agreed with the laboratory and predicted information. The in situ resistivity data taken at stations 5W, 10W, and 11 were nominally 1.5 to 2.5 orders of magnitude greater than the predicted resistivity. If these in situ data were correct, an untenable situation would prevail. Since factors other than resistivity affect precipitator characteristics, the efficiency data and, in particular, the outlet-field current density values suggest that the correct resistivity values are significantly lower than the in situ data indicate. The correlation among outlet-field current density, laboratory-measured resistivity, and predicted resistivity is encouraging.

The observation regarding these in situ resistivity data is not unusual. When surface resistivity dominates and conduction is principally dependent on charge carrying ions of limited concentration, in situ resistivity data are often unrealistically high. No serious effort to clarify this situation has been made. One can suggest several potential explanations for this occurrence. The point-plane, in situ, resistivity probe can collect a particle size distribution that is biased toward the coarse fraction. This reduces the surface area available for conduction, and if charge carrying ions such as sodium are disproportionately distributed among the finer sizes, current carrying ability is further lessened. Often a rather long time period occurs in depositing the ash in the probe under high current density. If conduction is dependent on sodium ions of finite concentration, the long-term, high-current-density deposition technique can distort the resistivity by developing a high resistivity layer depleted of sodium ions. Finally, if by some unusual circumstance the collected ash is wetted by condensed water which is subsequently evaporated, the measured resistivity will be incorrectly high. Clearly, this position regarding point-plane data deserves attention.

The data for Stations 2E, 3E, 7E, 12E, and 14E were obtained from cold-side precipitator operations collecting ash from eastern coals. Considering the precision of the measurements made and the slight deviations between laboratory and in situ environments, the data for stations 2E, 3E, 7E, and 12E stand reasonably free of criticism.

No laboratory resistivity data were available for the Station 14E review. The in situ resistivity value is an order of magnitude less than the predicted result. Although a desirable resistivity level was predicted, the outlet-field current density suggests that the in situ resistivity data are more nearly correct. The poor efficiency recorded was related to other circumstances.

The evaluation of the resistivity comparison can be summarized as follows:

- All of the laboratory resistivity measurements made under conditions simulating the in situ water and sulfur trioxide concentrations were in reasonable agreement with the predicted resistivity value.
- Although circumstances allow only qualitative interpretation, no flagrant disagreement occurred between outlet-field current density data and predicted resistivity.
- Resistivity determined in situ was in reasonable agreement with predicted resistivity in 6 out of 11 tests (55%). Several aspects of this undesirable situation were elaborated upon above.

CONCLUSIONS AND RECOMMENDATIONS

A bold step was taken in attempting to predict fly ash resistivity from input data consisting of the as-received, ultimate coal analysis and the chemical composition of the coal ash. Considering the imperfections in the measurements used in precipitator technology and the limited amount of laboratory data available with respect to environments containing sulfur trioxide, the subject evaluation of an initial resistivity prediction technique of this type is very favorable. However, serious discrepancies have been pointed out. These points and an awareness that some critical correlations used in the predictive method are based on limited information suggest the need for the following additional effort.

- A point-plane, in situ,resistivity probe and a laboratory resistivity test cell should be simultaneously evaluated in an environmental chamber with electrification techniques, temperature, fly ash composition, and water and sulfur trioxide concentrations as variables.

- With special attention to measurement precision, additional sulfur dioxide and sulfur trioxide data taken at the hot and cold sides of the air preheater are needed. These data are required to substantiate or alter the present method of determining the sulfur trioxide concentration used in the resistivity prediction and to justify the sulfur trioxide concentrations used in developing the laboratory data.

- The predictive technique should be evaluated using coals having high ash and/or moisture contents. These coals produce environments containing disproportionately high sulfur trioxide concentrations for a given sulfur content.

- Although the fly ash - coal ash compositional correlation has been good, it would be desirable to develop an objective method for establishing the ignition temperature for the crucible ashing of each coal.

- A broader laboratory resistivity data base must be established for the relationships among the variables: fly ash composition, temperature, and the environmental factors.

REFERENCES

1. Bickelhaupt, R.E. A Technique For Predicting Fly Ash Resistivity. EPA-600/7-79-204, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, August 1979.

2. Gooch, J.P. and Marchant, G.H., Jr. Electrostatic Precipitator Rapping Reentrainment and Computer Model Studies. EPRI FP-792 Volume 3, Electric Power Research Institute, Palo Alto, California, 1978.

3. Unpublished reports pertaining to field tests conducted by Southern Research Institute.

Table 1. Computer Printout of Resistivity Prediction
Station 3E

```
                                                       REQUIRED FOR COMBUSTION
                                                        MOLES/100 LB FUEL
           AS RECEIVED          MOLES PER              AT 100% TOTAL AIR
         ULTIMATE COAL           100 LB              -----------------------
           ANALYSIS               FUEL                 O2           DRY AIR
         -------------         ---------             ------         -------
C            62.44               5.199               5.199          24.747
H2            3.95               1.955               0.978           4.653
O2            8.27               0.258              -0.258          -1.228
N2            1.25               0.045               0.000           0.000
S             2.02               0.063               0.063           0.300
H2O          10.84               0.602               0.000           0.000
ASH          11.23               0.000               0.000           0.000

SUM         100.00               8.122               5.982          28.472


                                                REQ FOR COMBUSTION
                                                 MOLES/100 LB FUEL
                                                  @30% EXCESS AIR
                                                -----------------
                                                  O2       DRY AIR
                                                ------     -------
O2 AND AIR * 130/100 TOTAL                       7.777      37.014
EXCESS AIR                                                   8.542
EXCESS O2                                        1.795


                         PRODUCTS OF COMBUSTION
                ------------------------------------
                 TOTAL
                MOLES/100        % BY VOL         % BY VOL
                 LB FUEL        WET BASIS        DRY BASIS
                ---------       ---------        ---------
CO2                5.199          13.104           14.305
H2O                3.332           8.399            0.000
SO2                0.063           0.159            0.173
N2                29.286          73.814           80.582
O2                 1.795           4.524            4.939
SUM WET           39.675
SUM DRY           36.343


H2O                  8.4
SO2                 1730
SO3                  6.9

E                     10
```

Table 1. (Cont'd.)

```
                       CORRECTED
            ASH           ASH           ATOMIC
          ANALYSIS      ANALYSIS     CONCENTRATION
          --------      ---------    -------------
LI2O        0.03          0.03           0.049
NA2O        0.63          0.64           0.496
K2O         2.10          2.13           1.088
MGO         1.00          1.01           0.908
CAO         4.70          4.76           3.068
FE2O3       9.00          9.11           1.651
AL2O3      25.40         25.72           7.297
SIO2       53.30         53.98          21.648
TIO2        1.60          1.62           0.489
P2O5        0.21          0.21           0.031
SO3         0.77          0.78           0.176

SUM        98.74        100.00          36.901

SUM OF LITHIUM AND SODIUM ATOMIC CONCENTRATIONS                 0.55
SUM OF MAGNESIUM AND CALCIUM ATOMIC CONCENTRATIONS               4.0
IRON ATOMIC CONCENTRATION                                        1.7
POTASSIUM ATOMIC CONCENTRATION                                  1.09

TEMP 1000/T(K)  DEG K  DEG C  DEG F    RHO(VS)    RHO(VSA)
--------------  -----  -----  -----    -------    --------
     1.4         714    441    826     2.3E+08    2.3E+08
     1.6         625    352    666     1.7E+09    1.7E+09
     1.8         556    283    541     1.2E+10    1.2E+10
     2.0         500    227    441     8.3E+10    8.3E+10
     2.2         455    182    359     3.3E+11    2.9E+11
     2.4         417    144    291     3.6E+11    1.9E+10
     2.6         385    112    233     1.5E+11       **
     2.8         357     84    183     1.8E+10       **

**  EXISTING EXPERIMENTAL DATA DO NOT JUSTIFY COMPUTATIONS
    AT TEMPERATURES LOWER THAN 144 DEGREES C.

NOTE: BECAUSE THE PREDICTED RESISTIVITY VALUES ARE VERY
SENSITIVE TO SEVERAL FLUE GAS AND ASH COMPOSITIONAL FACTORS,
ONE MUST EXERCISE GREAT CARE IN THE SELECTION AND PREPARATION
OF COAL AND ASH SAMPLES. FURTHERMORE, THE QUALITY OF THE
QUANTITATIVE CHEMICAL ANALYSIS WORK IS OF GREAT IMPORTANCE.
IN ESTABLISHING THIS PROGRAM, THE AS-RECEIVED, ULTIMATE COAL
ANALYSES WERE OBTAINED USING ASTM D3176 PROCEDURE, AND THE
COAL ASH WAS PRODUCED USING ASTM D271 PROCEDURE FOLLOWED BY
A SECOND IGNITION AT 1050 DEGREES C + OR - 10 DEGREES C IN
STILL AIR FOR 10 TO 12 HOURS.
```

Table 2. Evaluation of Predicted Resistivity
General Information and Coal Analyses for Several Power Stations

STATION NUMBER	1W	2E	3E	4E	5W	6W
TEST DATE	7 AUG 75	15 JAN 76	2 MAR 76	27 APR 76	5 OCT 76	1 FEB 77
UNIT SIZE, MW	135	160	122	271	508	800
SCA of ESP, $m^2/m^3/sec$	98.8	49.8	50.2	76.4	117.2	60.2
$ft^2/ft^3/min$	504	254	256	390	598	307
COAL ANALYSIS AS RECEIVED						
PROXIMATE, wt. %						
Moisture	13.94	2.07	10.84	6.22	19.91	8.26
Volatile Matter	37.78	39.05	33.99	30.73	26.48	38.90
Fixed Carbon	43.07	47.91	43.94	50.20	42.16	43.56
Ash	5.21	11.00	11.23	12.85	11.45	9.28
Sulfur	0.41	3.28	2.05	0.95	0.43	0.45
ULTIMATE, wt. %						
Carbon	59.41	71.26	62.44	64.75	52.01	65.23
Hydrogen	4.24	5.01	3.95	4.11	3.53	4.25
Oxygen	15.33	5.87	8.27	9.42	11.55	11.52
Nitrogen	1.46	1.54	1.25	1.69	1.02	1.01
Sulfur	0.41	3.28	2.02	0.96	0.53	0.45
Moisture	13.94	2.04	10.84	6.22	19.91	8.26
Ash	5.21	11.00	11.23	12.85	11.45	9.28

Table 2. (Cont'd.)

STATION NUMBER	7E	10W	11W	12E	13W	14E
TEST DATE	17 SEPT 76	29 SEPT 77	19 OCT 77	8 DEC 77	21 JULY 77	15 SEPT 77
UNIT SIZE, MW	350	500	500	250	800	400
SCA of ESP, $m^2/m^3/sec$	33.3	172.9	96.0	158.0	60.2	34.7
$ft^2/ft^3/min$	170	882	490	806	307	177
COAL ANALYSIS AS RECEIVED						
PROXIMATE, wt%						
Moisture	11.68	13.44	18.67	8.41	12.34	4.71
Volatile Matter	31.06	31.69	38.14	16.90	37.81	33.64
Fixed Carbon	46.36	43.55	30.62	48.88	40.59	47.20
Ash	10.90	11.32	12.57	25.80	9.27	14.45
Sulfur	0.81	0.61	0.58	0.79	0.48	2.15
ULTIMATE, wt %						
Carbon	65.22	56.77	53.31	57.21	60.58	62.89
Hydrogen	3.87	4.09	4.36	3.74	4.16	4.47
Oxygen	6.21	12.48	9.44	3.03	11.78	9.89
Nitrogen	1.21	1.29	1.07	1.02	1.39	1.44
Sulfur	0.91	0.61	0.58	0.79	0.48	2.15
Moisture	11.68	13.44	18.67	8.41	12.34	4.71
Ash	10.90	11.32	12.57	25.80	9.27	14.45

Table 3. Evaluation of Predicted Resistivity

Fly Ash, Coal Ash, and Flue Gas Compositions for Several Power Stations

STATION NUMBER	1W		2E		3E		4E		5W		6W	
ASH COMPOSITION WEIGHT PERCENT	FLY ASH	COAL ASH	FLY ASH	COAL ASH	FLY ASH	COAL ASH	FLY ASH	COAL ASH	FLY ASH[a]	COAL ASH	FLY ASH	COAL ASH
Li_2O	0.02	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.02	0.02	0.01	0.01
Na_2O	0.29	0.27	0.55	0.49	0.67	0.63	0.43	0.44	1.38	1.28	1.78	1.89
K_2O	1.8	1.0	2.5	2.1	2.1	2.1	3.5	3.2	0.54	0.53	1.2	1.1
MgO	3.6	2.8	0.9	0.8	1.0	1.0	1.3	1.2	1.1	1.8	1.7	1.8
CaO	8.6	7.5	5.6	5.5	5.0	4.7	1.1	1.0	5.8	5.3	7.4	8.1
Fe_2O_3	5.9	6.0	24.4	24.1	13.1	9.0	7.2	7.4	6.1	2.5	5.0	5.7
Al_2O_3	23.7	15.2	18.3	19.2	21.8	25.4	28.4	28.4	13.2	13.7	23.9	20.2
SiO_2	51.9	65.3	45.1	41.6	50.2	53.3	53.8	53.3	70.8	73.6	56.4	57.9
TiO_2	1.3	1.2	1.3	1.6	2.0	1.6	1.8	1.9	0.9	1.2	2.1	1.0
P_2O_5	0.39	0.35	0.30	0.29	0.78	0.21	0.23	0.24	0.05	0.13	0.49	0.47
SO_3	1.2	0.58	1.9	4.7	2.3	0.77	0.50	0.15	0.50	0.63	0.40	2.0
TOTAL	98.7	100.2	100.9	100.4	99.0	98.6	98.3	97.3	100.4	100.7	100.4	100.2
LOI	0.8		4.0		10.9		3.5		1.0		0.1	
SOLUBLE SULFATE	0.7		0.9		1.6		0.3		0.5		0.3	
FLUE GAS COMPOSITION	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED
CO_2, vol %	13	13	15	13	13	13	15	13	13	13	14	13
O_2, vol %	7	5	5	5	5	5	5	5	6	5	4	5
H_2O, vol %	8.3	9.6	8.3	7.6	8.2	8.4	8.5	7.8	8.1	10.5	9.0	8.3
SO_2 ppm	262	440	3000	2380	2440	1730	755	800	480	570	350	380
SO_3 ppm	<1	1.8	9-12	9.5	6-9	6.9	2-3	3.2	<1	2.3	<1	1.5

---

a) About 8% of this ash was >0.18 mm (+80 mesh) and mostly carbon. It was removed prior to testing.

Table 3. (Cont'd.)

STATION NUMBER	7E		10W		11W		12E		13W		14E	
ASH COMPOSITION WEIGHT PERCENT	FLY ASH	COAL ASH	FLY ASH	COAL ASH	FLY ASH	COAL ASH	FLY ASH	COAL ASH	FLY ASH	COAL ASH	FLY ASH	COAL ASH[b]
Li_2O	0.05	0.05	0.02	0.01	0.02	0.02	0.04	0.04	0.01	0.01	0.04	
Na_2O	0.27	0.31	0.39	0.43	2.68	2.40	0.45	0.45	1.42	1.51	0.17	
K_2O	2.1	2.2	1.7	1.4	1.5	0.9	3.4	3.7	1.0	0.9	1.3	
MgO	0.9	0.9	2.6	2.5	1.8	1.4	1.3	1.4	1.8	1.9	0.5	
CaO	3.7	3.2	15.0	16.1	7.1	5.9	0.8	0.7	6.7	7.3	0.7	
Fe_2O_3	7.1	6.8	7.4	7.9	3.9	4.0	7.0	6.7	5.0	5.7	17.9	
Al_2O_3	29.3	29.4	18.6	19.0	17.8	16.1	27.2	27.6	25.5	21.6	24.4	
SiO_2	53.5	54.4	50.8	47.1	63.2	66.5	57.4	58.2	56.3	57.8	48.3	
TiO_2	1.8	1.6	1.0	0.8	1.5	1.3	1.7	1.7	1.0	0.5	1.3	
P_2O_5	0.20	0.33	0.8	0.6	0.2	0.2	0.2	0.10	0.31	0.3	0.41	
SO_3	0.7	1.6	0.7	5.0	0.5	1.1	0.1	0.2	0.71	3.5	1.7	
TOTAL	99.6	100.8	99.0	100.8	100.2	99.8	99.6	100.8	99.8	101.0	96.7	
LOI	7.5	---	0.8	---	1.4	---	6.0	---	2.6	---	7.8	---
SOLUBLE SULFATE	0.7	---	0.4	---	0.4	---	0.3	---	0.5	---	0.7	---
FLUE GAS COMPOSITION	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED
CO_2, vol %	ND	13	14	13	15	13	14	13	15	13	12	13
O_2, vol %	ND	5	6	5	5	5	5	5	5	5	7	5
H_2O, vol%	9.0	8.2	9.5	9.6	10.6	10.9	8.1	8.2	9.6	9.1	9.5	8.1
SO_2 ppm	600	740	510	580	570	570	570	739	430	429	1415	1810
SO_3 ppm	3-4	3.0	<1	2.3	<1	2.3	0.5	3.0	<1	1.7	7.0	7.2

---

b) Not determined (ND).

Table 4. Evaluation of Predicted Resistivity

Temperature, Resistivity, and Performance Data for Several Power Stations

STATION NUMBER	1W	2E	3E	4E	5W	6W
TEMPERATURE, °C	145	158	158	332	105[a]	350
RESISTIVITY, ohm•cm						
In situ, @ Spark	3.0×10^{11}	1.0×10^{10}	2.1×10^{10}	3.0×10^{10}	5.0×10^{11}	b
Laboratory, @ Spark	5.0×10^{11}	1.2×10^{10}	2.3×10^{10}	4.0×10^{9}	5.0×10^{10}	1.1×10^{9}
Predicted, @ 10 kV/cm	1.2×10^{11}	2.0×10^{10}	7.0×10^{10}	2.3×10^{9}	1.6×10^{10}	8.5×10^{8}
ESP EFFICIENCY, %	99.92	99.55	99.87	99.65	99.85	99.47
CURRENT DENSITY OUTLET FIELD, nA/cm^2	15	24	45	37	23	50[c]

STATION NUMBER	7E	10W	11W	12E	13W	14E
TEMPERATURE, °C	163	138	134	143	350	154
RESISTIVITY, ohm•cm						
In situ, @ Spark	2.7×10^{11}	6.9×10^{12}	7.0×10^{12}	3.0×10^{11}	1.8×10^{9}	3.0×10^{9}
Laboratory, @ Spark	2.2×10^{11}	2.0×10^{11}	2.2×10^{10}	5.0×10^{11}	2.0×10^{9}	b
Predicted, @ 10 kV/cm	5.0×10^{11}	6.0×10^{10}	1.4×10^{10}	2.3×10^{11}	1.4×10^{9}	4.0×10^{10}
ESP EFFICIENCY, %	e	(99.6)[d]	(99.8)[d]	(99.8)[d]	99.22	89
CURRENT DENSITY OUTLET FIELD, nA/cm^2	e	15	16	46	13	90

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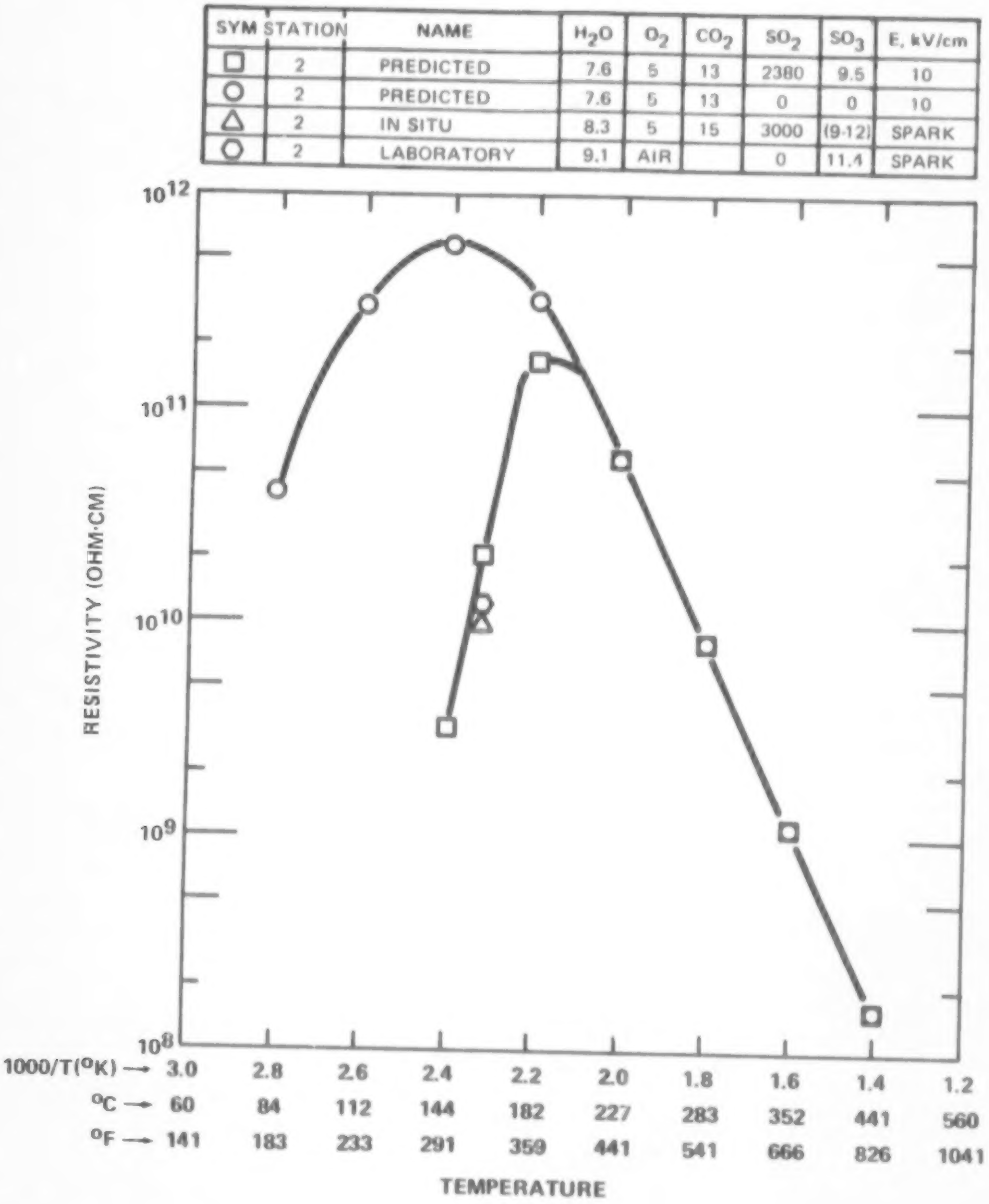
a) Test temperature below that of acquired laboratory data involving sulfur trioxide.
b) Not determined.
c) j-V curves indicate back-corona.
d) Typical only.
e) Not available.



SYM	STATION	NAME	H_2O	O_2	CO_2	SO_2	SO_3	E, kV/cm
□	2	PREDICTED	7.6	5	13	2380	9.5	10
○	2	PREDICTED	7.6	5	13	0	0	10
△	2	IN SITU	8.3	5	15	3000	(9-12)	SPARK
○	2	LABORATORY	9.1	AIR		0	11.4	SPARK

Figure 1. Predicted, in situ, and laboratory measured resistivity.

SO_3 CONDITIONING
FOR
IMPROVED ELECTROSTATIC PRECIPITATOR PERFORMANCE
OPERATING ON LOW SULFUR COAL

BY:

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This presentation deals with a case study of a particular utility's dilemma of having to choose an efficient and reliable air pollution control device to lower stack emissions on an existing unit. The paper traces the study from the time when excessive emissions required MW load deratings into the decision making process, the testing stage, and finally into the installation of SO_3 flue gas conditioning.

It points out why, in this particular case, SO_3 flue gas conditioning is a more reasonable choice than the installation of a new cold side precipitator or fabric filter baghouse. It clearly shows via test results supplied by a utility based in upstate New York that SO_3 flue gas conditioning enables units at their power plant to operate well within the legal standards enforced by the New York State Department of Environmental Conservation (NYSDEC).

SO_3 CONDITIONING FOR IMPROVED ELECTROSTATIC PRECIPITATOR PERFORMANCE OPERATING ON LOW SULFUR COAL

INTRODUCTION

This presentation deals with a case history concerning the upgrading of a two chamber, two field, twenty-six year old electrostatic precipitator. The utilities Unit 3 (boilers 4 and 5) is a steam electric generating unit rated at 57.7 MW. It has two steam boilers and until 1971 was equipped with only mechanical dust collectors. The existing #4 & #5 precipitator at the station is the original #6 precipitator (see Figure 1) and has been in operation since 1953. In 1971, this precipitator was optimized by increasing the TR capacity and converted to serve #4 & #5 boilers with a total gas volume of 270,000 ACFM at 330°F and an efficiency of 97.5% following mechanical collectors.

In 1976 the utility installed an opacity monitor on Unit 3 stack and from this addition came the realization that Unit 3 emissions were often higher than the 20% opacity limit. It was significant that the only time Unit 3 was in violation of the 20% opacity limit was when low sulfur, high ash coal was being burned. When high sulfur, low ash coal was introduced into the system the opacity would eventually drop significantly. These results pointed to one possible problem; high resistivity fly ash.

SOLUTIONS

The utility prepared a list of possible solutions to alleviate the emission problems when firing low sulfur coal on Unit 3. The list included: (1) a new electrostatic precipitator; (2) a new fabric filter baghouse; or (3) upgrading the existing mechanical and electrostatic precipitators along with the addition of flue gas conditioning.

1. The installation of a new cold side electrostatic precipitator on boilers #4 and #5 would have had to be designed to meet today's present coal and ash qualities and the precipitator would have to contend with collecting the low sulfur coal, high resistivity fly ash while meeting both EPA particulate and SO_x emission regulations. One of the most important factors in precipitator design and operation is the fuel analysis with sulfur being the most critical. One to three percent of the sulfur content of the coal is converted to SO_3 in the economizer portion of the boiler. The SO_3 generated is accepted as the prime element controlling resistivity for most coals. The fact that the EPA considers sulfur emissions to the atmosphere undesirable sets up an opposition of interests. On one side the EPA requires low sulfur emissions and on the other the industry needs sulfur in the fuel to condition the fly ash so that it can be precipitated. When low sulfur fuels are fired, high resistivity fly ash is often the result, and very large precipitators are required to efficiently remove the fly ash.

The utility has had some very unsatisfactory experiences with cold side electrostatic precipitators ostensibly designed for low sulfur coal (600 square feet of surface collecting area per 1000 ACFM) in the past because of high resistivity problems. This was the major reason that they did not pursue the installation of a cold side precipitator. In addition, the total estimated cost for the installation of an electrostatic precipitator to handle 270,000 ACFM of flue gas at 330°F was approximately $5,400,000 with a lead time of 24-36 months.

2. The installation of a fabric filter baghouse on boilers #4 and #5 appeared to be a more viable solution than an electrostatic precipitator in this particular application with low sulfur coal. A baghouse is totally unaffected by the high resistivity fly ash. Changing of fuels on a daily basis will not affect the operation of the baghouse. The baghouse also has the advantage of 99.9+% collection efficiency. Should the EPA in the future require even stricter standards, the baghouse would be in compliance without modification. Two major drawbacks of the fabric filter baghouse are the life of the collecting bags and the increased pressure drop across the system.

The major reasons for excluding the fabric filter baghouse from the possible solution list were the cost which was $3,200,000, the 16-18 months delivery, and the fact that new I.D. fans would have to be purchased. The total cost of replacing the I.D. fans was approximately $1,100,000.

3. The third and final solution was to upgrade the existing mechanical collector and electrostatic precipitator and install flue gas conditioning. The mechanical collecting cones and vanes had been in service for 30 years without a changeout. The cones and vanes were in poor condition and were in need of immediate replacement. As far as the electrostatic precipitator was concerned, it was in good operating condition except that it needed new discharge electrodes.

So far, so good, except for flue gas conditioning. The utility experienced extensive testing at another station with a liquid additive conditioning agent which required injection upstream of the air heater to vaporize the conditioning agent. The results of the conditioning agent tests proved to be negative and extremely costly in terms of downtime and material cost. The air heater was plugged after two weeks of operation and the emissions were not reduced while injecting the additive. Needless to say, the utility's view of flue gas conditioning was not very optimistic after this episode, but they continued to investigate other methods.

From correspondence with other major utilities it was discovered that they were using, quite successfully, SO_3 flue gas conditioning to help maintain particulate collection efficiency and opacity requirements. After consulting these major electric utilities, field trips were conducted to observe the systems in operation. The utility was quite impressed with the results they saw. The major point that was made clear by the other operating utilities was that SO_3 injection will only allow the precipitator to perform as well as they would with high sulfur coal, and not better than the design efficiency which for #4 and #5 precipitator, was 97.5%.

After evaluating the above solutions, it was decided to conduct efficiency tests on Unit 3 to determine if #4 and #5 precipitator with SO_3 conditioning could consistantly stay under the 20% opacity limit.

TEST RESULTS PRIOR TO GAS CONDITIONING

The testing procedure was set up into two basic categories, high and low sulfur coal tests. The first series of tests were conducted in January 1978 on boiler #5 while burning low sulfur coal prior to the changeout of the mechanical dust collectors. (See Table 1.) The efficiency averaged 73% for these tests with the outlet emission rate at 619 lb/hr. The maximum allowable emission rate for boiler #5 set forth by the New York State Department of Environmental Conservation was 84 lb/hr. The inlet dust loading of 2,523 lb/hr indicated that the mechanical collectors would have to be replaced to help lower the inlet grain loading.

During the annual #5 boiler outage all 297 collecting cones and vanes were replaced with new ones and efficiency tests were conducted while burning high sulfur coal in May 1978. (See Figure 2.) These tests highlighted two important facts. The mechanical dust collectors significantly lowered the inlet dust loading by 841 lb/hr and the high sulfur coal enabled the precipitator to perform higher than the design efficiency of 97.5%. (See Table 2.)

FLUE GAS CONDITIONING

Based on the test results it was decided to rent an SO_2 source flue gas conditioning system and install a test set up on #5 boiler precipitator. The cost of the rental system was $20,000/month with 50% of the rental cost applied to the purchase of a new system.

The equipment which was shipped to the station was a liquid SO_2 source system consisting of a liquid SO_2 vaporizer, air filter, fan, SCR controlled electric heaters, SO_2-SO_3 catalytic converter and injection probes. The system was designed to inject 40 ppm of SO_3 into 135,000 ACFM of flue gas at 330°F. A 40 ton SO_2 tank was rented as temporary storage for the liquid SO_2. (See Figure 3.) Process instrumentation provided fail-safe operation and automatic adjustment of SO_3 production in response to boiler load.

TEST RESULTS WITH SO_3 GAS CONDITIONING

The rental SO_2 source flue gas conditioning system was delivered to the station in early October 1978 and placed in service November 1, 1978. However, prior to the start-up some efficiency tests were conducted while burning low sulfur coal in boiler #5. All these efficiency tests were necessary as the stack mounted opacity monitor recorded both #4 and #5 precipitator readings. The test results indicated that the mechanical collectors were definitely helping to lower the grain loading to the electrostatic precipitator. However, the outlet dust loadings were far worse than any other test results recorded to date. (See Table 3.)

The same quality low sulfur coal was used in the tests when the SO_3 system was placed in operation. The utility waited 12 days to completely condition the fly ash. Improved electrical readings on the precipitator were observed during this time. (See Table 4.) At this point (14) efficiency tests were conducted to determine the effectiveness of SO_3 injection at different injection rates. (See Table 5.) Looking at tests one through four, the average efficiency equalled the average of all of the high sulfur coal tests which was 97.7%. It was quite clear from looking at the remaining tests on Table 4 that as the SO_3 injection rate decreased, so did the efficiency of the precipitator.

The utility was so impressed by the results of the SO_2 source test unit that they contracted to rent the unit for a five month period to permit increase of the MW load generation.

CONCLUSION

The final decision to install a permanent SO_2 source flue gas conditioning system was based solely on the performance of the five month rental system at the test station. The rental system was revised to inject SO_3 into #4 precipitator which also shares Unit 3 stack. This enabled the station to obtain accurate opacity readings while SO_3 was being injected. The opacity readings rarely ever exceeded 20% and when it did it occurred due to insufficient liquid SO_2 supply.

The permanent flue gas conditioning system had one major change over the rental system; the converter and air heaters were not mounted on the motor control skid, but were mounted on their own skid. (See Figure 4.) The converter and air heater skids are to be located at the point of SO_3 injection to allow for less hot gas piping and less temperature loss of the SO_3/air mixture. The permanent system is to be in operation by July 1, 1979. The cost of the total installed system was approximately $460,000.

After evaluating cold precipitators and baghouses, the utility was convinced that a small 296 SCA precipitator which had been upgraded combined with SO_3 flue gas conditioning, would be a reliable and cost efficient solution to meeting federal particulate emissions while burning low sulfur pulverized coal.

Table 1 SUMMARY OF PRECIPITATOR TEST RESULTS WHILE BURNING LOW SULFUR COAL PRIOR TO CHANGEOUT OF MECHANICAL DUST COLLECTORS (TEST CONDUCTED BY THE UTILITY)

TEST	INLET			OUTLET			EFFICIENCY %
	GR/SCF	LB/HR	LBS/10^{6}BTU	GR/SCF	LB/HR	LBS/10^{6}BTU	
1	3.99	2,881	8.12	1.09	714	2.22	72.7
2	2.48	2,583	5.05	.63	595	1.28	74.6
3	2.02	2,104	4.11	.58	548	1.18	71.3
AVG	2.83	2,523	5.76	.77	619	1.56	72.9

TYPICAL COAL ANALYSIS

PROXIMATE ANALYSIS	AS RECEIVED
MOISTURE, %	8.26
VOLATILE, %	19.21
FIXED CARBON, %	52.06
ASH, %	20.47
SULFUR, %	1.31
HEATING VALUE, BTU	10,366

Table 2 SUMMARY OF TEST RESULTS WHILE BURNING HIGH SULFUR COAL AFTER CHANGE OUT OF MECHANICAL DUST COLLECTORS
(TESTS CONDUCTED BY AN INDEPENDENT CONSULTANT)

TEST	INLET			OUTLET			EFFICIENCY %
	GR/SCF	LB/HR	LBS/10^6BTU	GR/SCF	LB/HR	LBS/10^6BTU	
1	1.37	1063	2.85	.078	58.7	.162	94.5
2	1.84	1387	3.88	.048	34.4	.101	97.5
3	1.86	1439	3.82	.042	31.3	.090	97.8
4	2.11	1661	4.51	.037	30.5	.083	98.2
5	1.91	1453	4.34	.041	30.8	.092	97.9
6	2.81	2212	6.05	.046	36.3	.099	98.4
7	2.42	1988	5.07	.050	41.3	.102	97.9
8	2.33	1880	4.84	.049	39.3	.106	97.9
9	2.56	1927	5.36	.044	32.1	.093	98.3
10	2.36	1807	4.94	.035	27.4	.076	98.5
AVG	2.16	1682	4.57	.047	36.2	.100	97.7

TYPICAL COAL ANALYSIS

PROXIMATE ANALYSIS AS RECEIVED	
MOISTURE, %	7.11
VOLATILE, %	26.31
FIXED CARBON, %	53.40
ASH, %	13.18
SULFUR, %	2.56
HEATING VALUE, BTU	12,136

Table 3 SUMMARY OF TEST RESULTS WHILE BURNING LOW SULFUR COAL WITH NO SO_3 INJECTION AFTER CHANGE OUT OF MECHANICAL DUST COLLECTORS (TESTS CONDUCTED BY AN INDEPENDENT CONSULTANT)

TEST	INLET			OUTLET			EFFICIENCY %	SO_3 PPM
	GR/SCF	LB/HR	LBS/10^6BTU	GR/SCF	LB/HR	LBS/10^6BTU		
1	1.90	1397	3.77	.747	529	1.58	60.64	0
2	2.16	1589	4.72	.624	474	1.34	71.13	0
3	2.03	1490	4.42	1.521	1158	3.30	25.04	0
4	2.42	1905	5.46	1.225	974	2.76	49.40	0
5	2.40	1891	5.33	.518	419	1.07	78.44	0
AVG	2.18	1654	4.74	.927	711	2.01	56.93	0

TYPICAL COAL ANALYSIS

PROXIMATE ANALYSIS AS RECEIVED	
MOISTURE, %	9.63
VOLATILE, %	18.89
FIXED CARBON, %	52.67
ASH, %	18.81
SULFUR, %	1.38
HEATING VALUE, BTU	10,568

Table 4 ELECTRICAL READINGS OF #5 PRECIPITATOR WITH AND WITHOUT SO_3 INJECTION

1. WITHOUT SO_3 INJECTION, 10/23/78

	INLET	OUTLET
AC AMPS	20	30
DC MA	100	100
PRIMARY VOLTAGE	190	190

2. WITH SO_3 INJECTION, 11/12/78

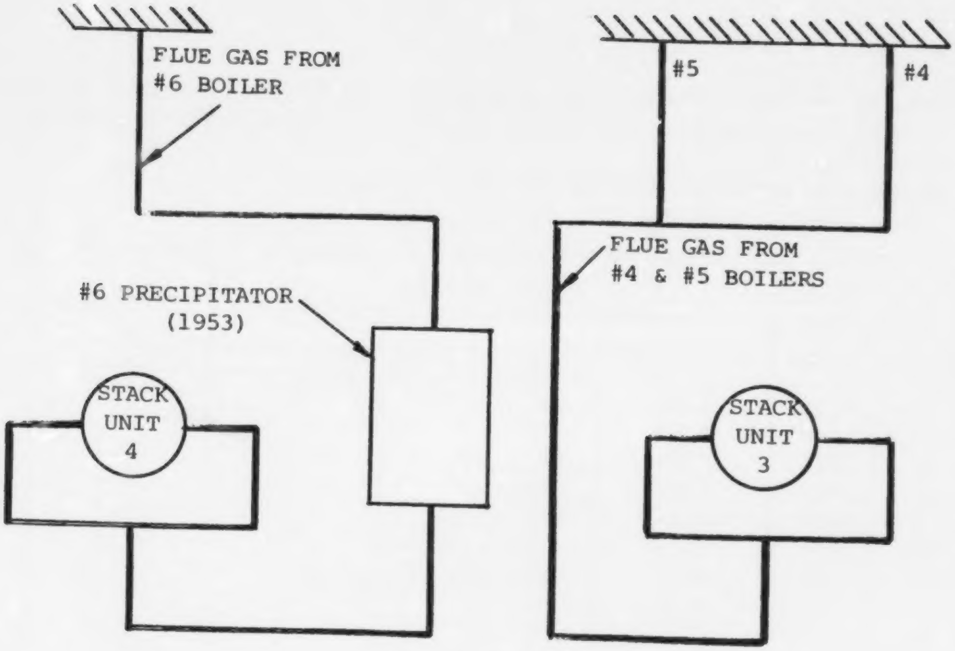
	INLET	OUTLET
AC AMPS	80	135
DC MA	500	800
PRIMARY VOLTAGE	270	310

Table 5 SUMMARY OF PRECIPITATOR TEST RESULTS WHILE BURNING LOW SULFUR COAL WITH SO_3 GAS CONDITIONING AFTER CHANGE OUT OF MECHANICAL DUST COLLECTORS
(TESTS CONDUCTED BY AN INDEPENDENT CONSULTANT)

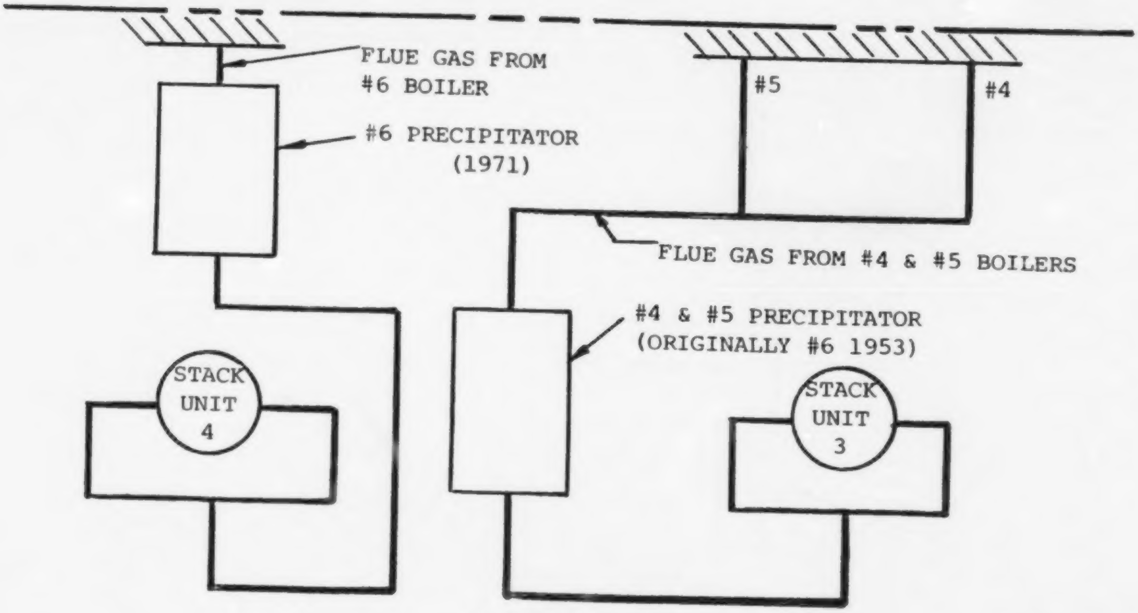
TEST	INLET			OUTLET			EFFICIENCY	SO_3
	GR/SCF	LB/HR	LBS/10^6BTU	GR/SCF	LB/HR	LBS/10^6BTU	%	PPM
1	2.74	2195	6.06	.045	33.7	.117	98.4	24
2	2.07	1740	4.89	.031	24.5	.070	98.5	24
3	1.18	1050	2.56	.047	38.2	.015	96.1	24
4	2.23	1887	4.94	.050	38.8	.111	97.8	24
5	1.91	1623	3.94	.051	38.7	.111	97.3	16
6	1.95	1676	3.84	.051	40.2	.108	97.4	16
7	2.09	1727	4.11	.078	60.5	.172	96.3	16
8	2.07	1774	4.16	.097	71.2	.206	95.3	16
9	1.94	1674	3.86	.100	79.4	.199	94.8	12
10	1.96	1635	3.93	.111	85.1	.252	94.3	12
11	2.00	1640	3.89	.127	87.7	.264	93.7	12
12	1.93	1608	3.87	.133	98.3	.247	93.1	12
13	1.94	1541	3.69	.103	78.0	.192	94.7	8
14	2.48	2121	5.33	.059	49.5	.136	97.6	8
AVG	2.04	1707	4.22	.077	58.8	.157	96.1	--

TYPICAL COAL ANALYSIS

PROXIMATE ANALYSIS AS RECEIVED	
MOISTURE, %	12.63
VOLATILE, %	24.19
FIXED CARBON, %	48.57
ASH, %	14.61
SULFUR, %	1.37
HEATING VALUE, BTU	10,345



ORIGINAL LAYOUT
(1953)



PRESENT LAYOUT
(1979)

Figure 1 SCHEMATIC OF UNITS 3 & 4
(PRESENT AND ORIGINAL LAYOUTS)

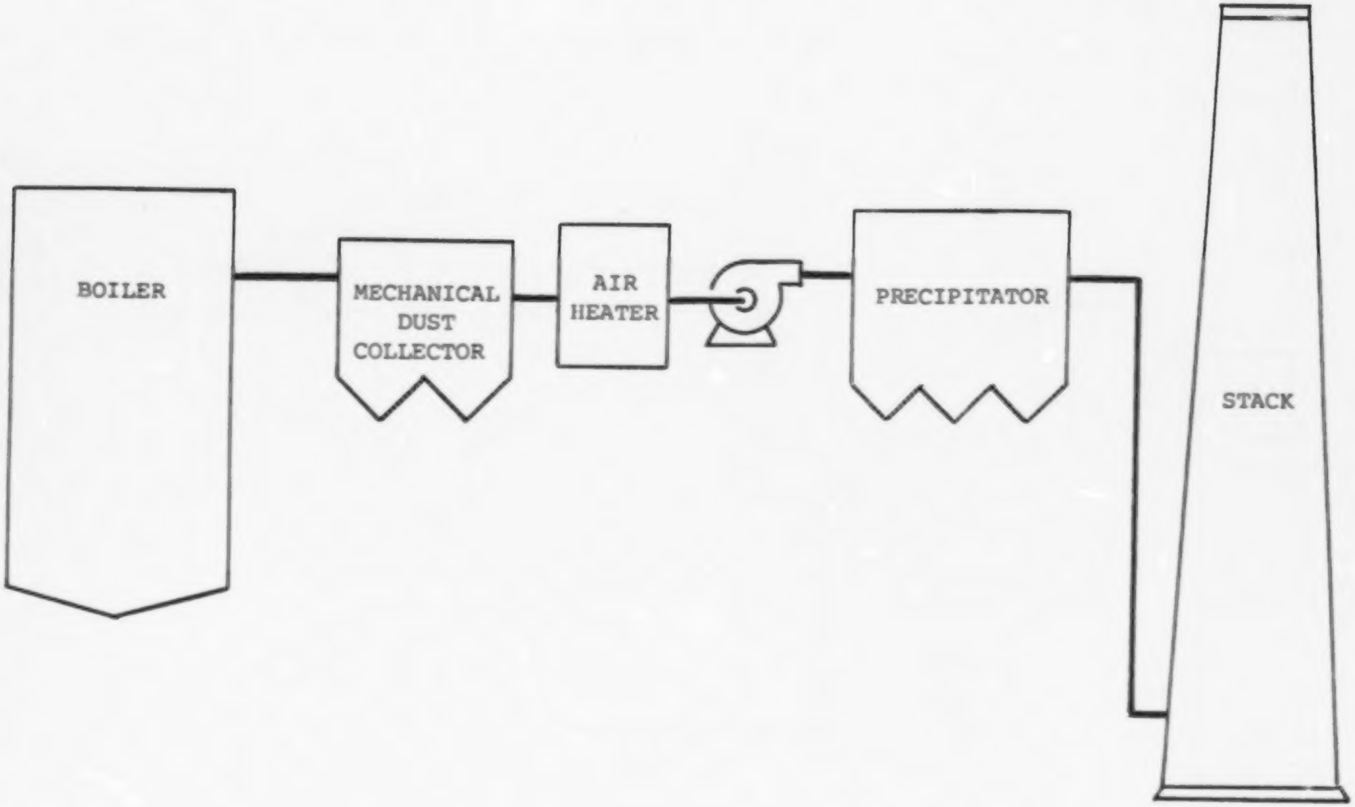


Figure 2 SCHEMATIC OF BOILER #5 GAS FLOW

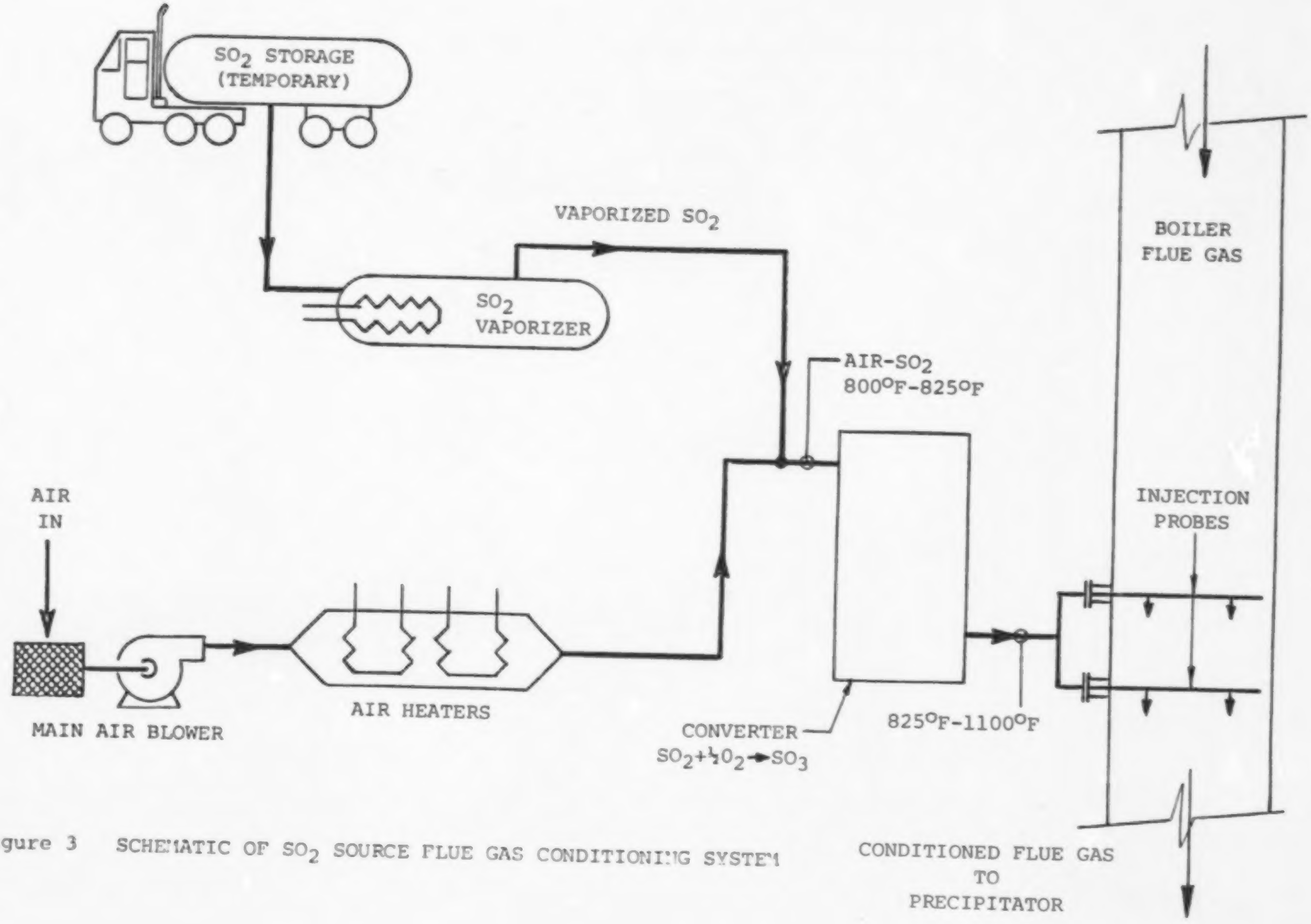


Figure 3 SCHEMATIC OF SO_2 SOURCE FLUE GAS CONDITIONING SYSTEM

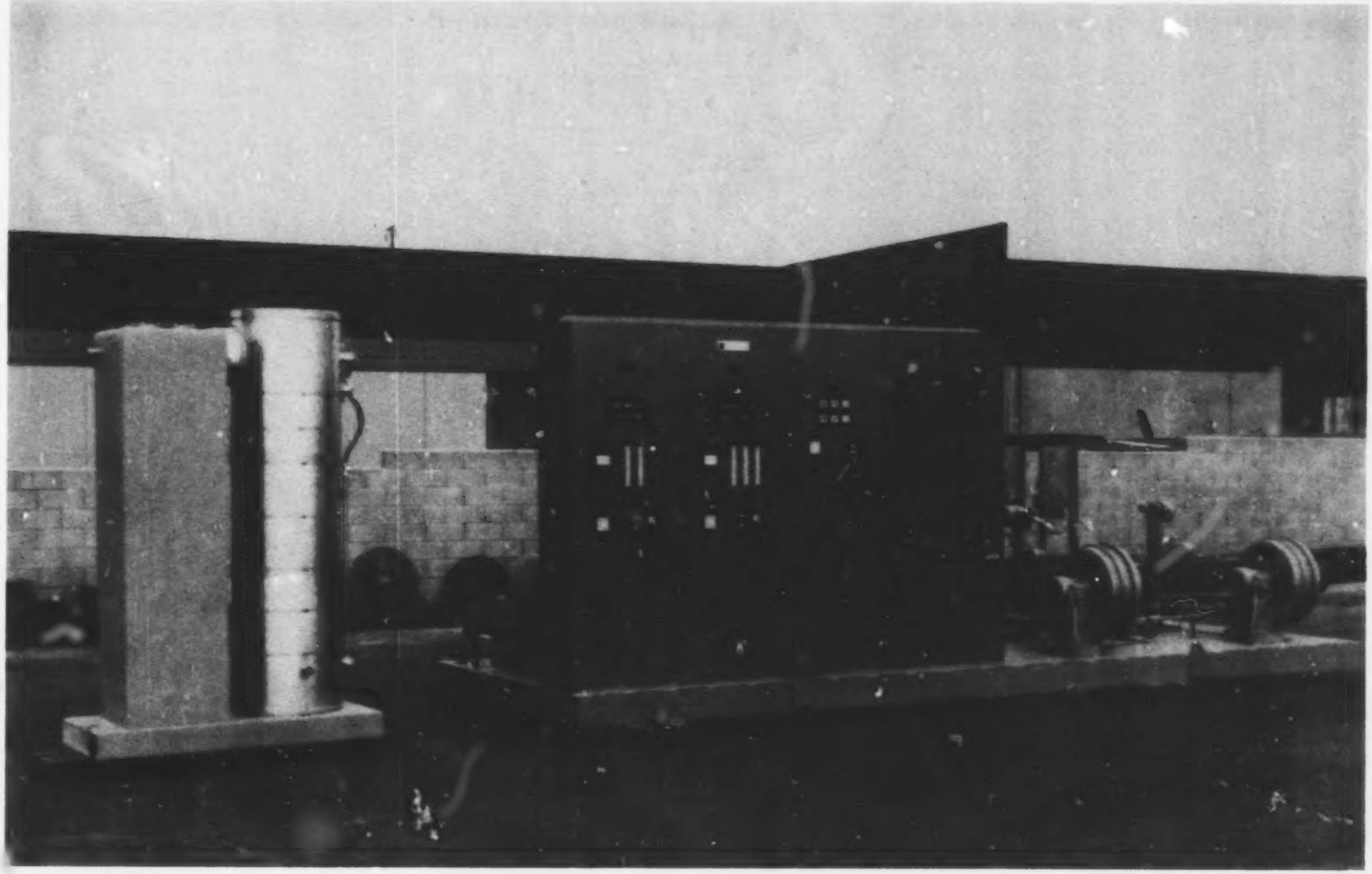


Figure 4. PERMANENT GAS CONDITIONING EQUIPMENT FOR #4 & #5 PRECIPITATORS

DOES SULPHUR IN COAL DOMINATE FLYASH COLLECTION IN ELECTROSTATIC PRECIPITATORS?

by

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It is commonly believed that the sulphur content of a coal has a profound influence on the efficiency with which its flyash is collected in an electrostatic precipitator. This question is discussed from theoretical and practical viewpoints and the evidence for and against examined. The discussion necessarily ranges over such topics as the surface chemistry of flyash, forms of sulphur in coal, correlation and causation, the measurement and interpretation of electrical resistivity, precipitation temperature, and the role of competing variables such as particle size and voltage. Precipitation data obtained in the authors' laboratory are used to show the extent to which low-sulphur coals can be accused of generating difficult flyashes. It is concluded that sulphur in coal is a misleading indicator of flyash behaviour and is unreliable for estimating precipitator size for a specified performance. At cold-side temperatures even low sulphur coal produces flyash carrying a conducting film of sulphuric acid, but this mechanism is not available at hot-side temperatures where volume conduction must be relied upon to avoid electrical difficulties in the precipitator. Such volume conduction may be impeded by the normal coatings of lime or alumina on flyash particles.

DOES SULPHUR IN COAL DOMINATE FLYASH COLLECTION IN ELECTROSTATIC PRECIPITATORS?

1. INTRODUCTION

There must be few engineers and scientists acquainted with the technology of electrostatic precipitation who do not accept that the collection of flyash is adversely affected by a low sulphur level in the parent coal. This belief has been expressed in countless publications in recent years, usually without support - as if there were no longer a need for any. The enquiring newcomer to this aspect of precipitation technology may well be dismayed with the scarcity of consistent information, which is disappointing in a matter of such economic importance as the proper sizing of precipitators, given that the use of low-sulphur coals is nowadays being enforced or encouraged.

In North America one may suspect that design engineers have placed reliance on the set of curves published by Ramsdell (1973)[1] relating required precipitator size and collecting efficiency at selected coal sulphur levels. The curves, which are claimed to reflect extensive full-scale data, imply clearly and quantitatively that the lower sulphur levels incur a considerable penalty in precipitator size for a given performance. Although probably hundreds of precipitators have been built and tested since the curves were made public, there seems to be no attempt to compare measured performances with those predicted, an omission which may give reassurance to the convinced but could seem suspicious to the sceptic. In Britain, Barrett (1971)[2] drew on the results of 109 collection efficiency tests from 23 power plants and analysed their multiple correlations to show that coal sulphur was positively correlated to effective migration velocity. Although it is uncertain whether the tests selected for examination were all independent of each other and representative of the whole situation (see later), the analysis stands as evidence that coal sulphur has a significant association with precipitator efficiency - at least under British conditions. Unlike the Ramsdell curves the Barrett study did not reveal an overriding influence of coal sulphur, which simply emerged as one of several factors in precipitator performance.

Australian electric utilities have been fuelled for decades by pulverized coals low in sulphur, largely because there is little else. While this means that Australia has accumulated almost no experience with controlling sulphur oxides emissions, the opposite is the case with flyash precipitation. So far as the present authors are aware, there never has been a well-founded body of Australian evidence or opinion that flyash from low sulphur coals is invariably difficult to collect in precipitators. Rather have precipitation engineers observed repeatedly that coals with the same low-sulphur level (say 0.5%) can generate flyashes of widely differing precipitabilities, from faultless in some cases to feeble in others.

For several years it has been passé among devotees in Australia to blame low-sulphur coals for difficult flyash, with the result that precipitation research and development have acquired an emphasis and a progression quite different from any seen elsewhere. It is the purpose of this paper to examine the circumstances of flyash precipitation in the particular context of coal sulphur levels and to put the entire question into perspective.

2. WHY SHOULD COAL SULPHUR AFFECT FLYASH COLLECTION?

The authors do not know of a closely-argued answer to the above question in the literature, and they offer the following rationale in descriptive language as a base for subsequent development. A number of the steps in the argument should be familiar to the combustion chemist but they have not appeared before in this particular context.

For the most part the sulphur in coal is present as heavy metal sulphide (e.g. pyrite) or bound organically (in macromolecules of vegetable and animal origin). Some sulphur may be present as inorganic sulphate (e.g. gypsum). When the coal is burned in the usual excess of oxygen (i.e. of air), the sulphide and the organic sulphur are oxidized to sulphur dioxide, and inorganic sulphate will be decomposed at least partially to sulphur trioxide and sulphur dioxide. As the flue gas (containing sulphur oxides) cools on passing from the flame through the passages of the combustion chamber and the other equipment, opportunity arises to convert a small proportion (often considered about 1%) of the sulphur dioxide to trioxide. While there is probably ample catalytic surface in the plant to secure the formation of sulphur trioxide, the flyash itself may share in the process and indeed may take the full burden if no other effective area is available. In any event at some elevated temperature below the normal boiling point of sulphuric acid (338°C) the sulphur trioxide and water vapour (the latter typically 5 - 10% of the flue gas) combine and sulphuric acid begins to condense on the electrically-insulating nuclei provided by the suspended flyash. In this way the flyash surface has the opportunity to become conducting by the time it reaches the entrance to the precipitator at 110 - 250°C (note that this temperature range is too high to support a liquid film of sulphurous acid, so that sulphur dioxide is itself useless for conferring any surface electrical conductivity on the flyash). It should be noted that above the evaporation temperature of sulphuric acid (say at $>300^\circ$C) the flyash has no opportunity to receive surface conduction from coal sulphur and therefore this coal property has no relevance to so-called hot-side precipitation.

Confining attention to cold-side precipitation, the next step requires the assumption that the amount of sulphur trioxide available to make the flyash conducting passes from adequate to inadequate as the coal sulphur level is decreased from typical higher values to low values (say from 2½ - 5% to below 1%). If the flyash has too low a conductivity (i.e. too high a resistivity), this constitutes an impediment to electrostatic precipitation by mechanisms that are known (Goard and Potter (1974)[3]) and collection efficiency must fall accordingly. Thus, if the above assumption holds (and provided sulphur trioxide is the only origin of flyash conduction), then low-sulphur coals should cause poor precipitation and the flyash should exhibit a resistivity above that which causes an impediment to precipitation (popularly supposed to be $10^{8.3}$ ohm-m, following White (1963)[4], but $10^{9.5}$ ohm-m is also supportable (Potter (1978)[5]). A corollary to this argument states that the low-sulphur impediment should be removed by the addition of sulphur trioxide (or of its equivalents, sulphuric acid or oleum) to the flue gas.

3. TO WHAT EXTENT SHOULD COAL SULPHUR AFFECT FLYASH COLLECTION?

To answer this question we observe that modification of flyash resistivity is the sole suggested mechanism by which coal sulphur influences precipitator performance and then only at cold-side temperatures (approximately 110 - 250°C). The significance of this observation is that once a resistivity impediment is removed (say by sulphur trioxide) further improvement of collection efficiency cannot be expected. Thus, based on the mechanism described above, and assuming a dominant role for coal sulphur (or of sulphur trioxide added to the flue gas), its anticipated effect is an initial progressive rise in collection efficiency as sulphur level increases, followed by a diminishing effect as a constant upper value of efficiency is reached above a certain sulphur level. Above this the resistivity continues to be decreased below the impediment limit ($10^{8.3}$ - $10^{9.5}$ ohm-m, see above), and at some higher sulphur level the possibility arises of lowering the flyash resistivity too much, that is to below about 10^{3} ohm-m where the collection efficiency falls on account of the electrodispersion effect encountered under these conditions (Paulson et al (1978)[6]).

There could also be a dependence of the expected sulphur effect on the amount and particle size of the ash generated by the coal, and two situations may be discerned. First, if the ash surface has little or no power to catalyse the formation of sulphur trioxide in the time available before the precipitator is reached, then an increase in ash content or a lessening of particle size (on passing from one coal to another at constant sulphur level) will result in the available sulphur trioxide being spread more thinly over the total ash area and a reduced benefit may be expected from coal sulphur. Thus, in this situation coals high in fine ash may have nothing to gain from sulphur at any realistic level, and there may be little precipitation contrast between low and high sulphur coals. On the other hand a good catalytic flyash may succeed in satisfying all its sulphur trioxide requirements no matter how great an area of incombustible residue the coal may produce, in which case the sulphur content of the coal would be of minor concern and even the lowest levels may not impede precipitation.

It is relevant to compare these expectations with the corresponding indications from the Ramsdell and the Barrett approaches described above. In the Ramsdell data the precipitation efficiency at 150°C is shown steadily increasing with coal sulphur level up to 3.0% sulphur where the data cease. It is not clear, however, by what mechanism the precipitation improves above 2% sulphur, since supporting graphs show that above this level the flyash resistivity lies in the "ideal precipitation zone" below 10^{8} ohm-m. The Barrett data are presented in terms of migration velocity rather than collection efficiency and show that the penalty to precipitator performance diminishes as the coal sulphur increases. The data cease at 3% sulphur, but were they to continue beyond this it seems that the performance would have no impediment from coal sulphur above approximately 5%. To this extent the Barrett data reflect the expectation deduced above, but the author himself warns of extrapolating his data. Neither Ramsdell nor Barrett indicates any dependence of the sulphur effect on ash yield or flyash size. Ramsdell alone suggests that the sulphur effect is temperature-dependent and asserts that it should have disappeared at hot-side temperatures (315°-425°C) as explained above.

An interesting aspect of the Barrett data arises from the suggestion that the results originated from precipitator acceptance tests. Such tests have a habit of giving efficiency results conforming to the design value, so that, if the sizes of the precipitators were originally computed by the manufacturer with some allowance for coal sulphur level, then this allowance will tend to persist as a partial correlation to be found in the acceptance data.

4. WHAT IS THE PRACTICAL EVIDENCE ON COAL SULPHUR AND FLYASH COLLECTION?

Previously published work on precipitation efficiency and coal sulphur has already been reviewed, and much of it was found inconsistent or inadequate (Potter (1978)[5]). More evidence has accumulated since, particularly an extension of the authors' studies and another set of observations from English electric utilities. In this latter work (Sochaczewski (1978)[7]), which to the authors' knowledge offers the only practical data definitely following the expected pattern described in Section 3 above, twenty four experimental points cover the sulphur range 0.6 - 5.1% and the effective migration velocity rises linearly from 6.4 to 14.7 $cm\ s^{-1}$ with only minor scatter, there being no further rise above 2.5% sulphur. Private communication with the author has disclosed that the four points at and below 1.0% sulphur originated from two power plants, and that the twenty remaining points (covering sulphur levels at and above 1.1% and collection efficiencies from 93.3 to 98.8%) were obtained at a third plant "during routine performance checks carried out under day-to-day operating conditions". All the tests were done at 130 - 150°C at gas flow rates within ± 10% of design and at the optimum voltages and currents of the precipitators (at least three in number). Presumably no flue gas additives were used. Particle size information was not available, but it would be remarkable if there were no significant differences. It is also not clear how many unrelated coals were tested, but the four points for coal below 1.0% sulphur suggest two unrelated coals, and the remaining data (20 points) are consistent with three unrelated coals being tested (one having 5%S, and the others 1.1% S and 2.8% S plus accidental blends of these last two). It is possible, therefore, that the English data were obtained from tests on five unrelated coals. The significance of this number of coals and of studies on coal blends emerges from later discussion, but it appears that the English information requires more detail and amplification before its meaning becomes clear.

In an earlier publication reference was made to the authors' fully comparative work at 120°C on 23 unrelated Australian coals using a pilot-scale combustion and precipitation rig with a record of concordance with full-scale results (Paulson (1974)[8]). This work has now been extended to include 43 unrelated coals, combining the results from two different pilot-scale rigs known to yield results in agreement. The experimental data were sufficiently comprehensive to allow efficiencies and migration velocities at constant voltage or current or at maximum voltage to be plotted against measured levels of any of the forms of coal sulphur. The precipitator performance could also be expressed as precipitator size (i.e. specific collecting area) for a selected flyash emission at maximum voltage with adjustment to 15% ash, and these figures were also plotted against coal sulphur parameters (Figure 1).

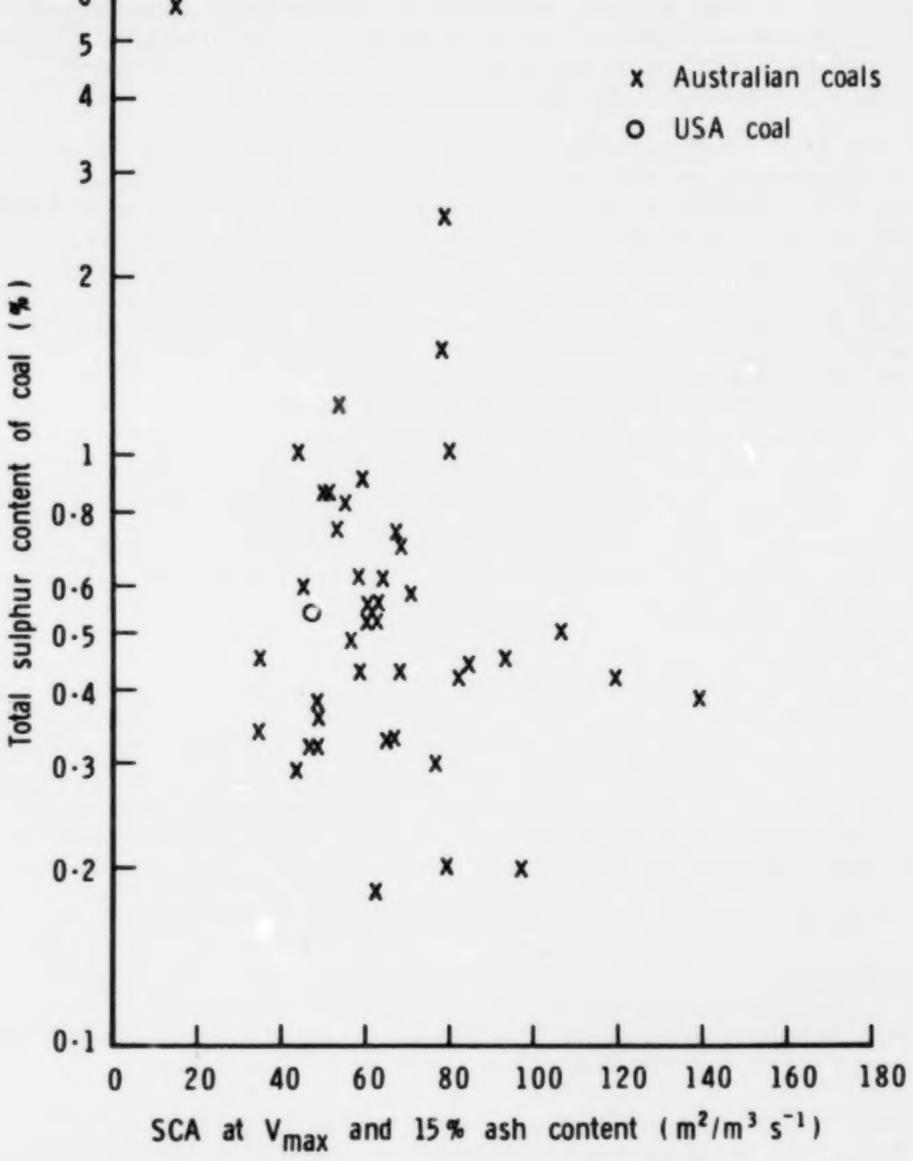

FIGURE 1. PLOT OF TOTAL COAL SULPHUR AGAINST SPECIFIC COLLECTING AREA AT 120 °C FOR A FLY-ASH EMISSION OF $0{\cdot}23\ g\ m^{-3}$ STP FOR 43 UNRELATED AUSTRALIAN COALS
(Data obtained at maximum voltage and normalized to 15% ash)

In addition an attempt was made (Figure 2) to allow for any scatter attributable to variations in flyash surface area among the coals by plotting precipitator performance against a modified coal sulphur parameter, namely, "(total coal sulphur x mass median diameter)/ash content." (See Appendix 1.) In no case was any semblance of a reasonable correlation found, and our former conclusion is strengthened that in Australia at least, no reliance can be placed on an association between any coal sulphur parameter and any measure of precipitator performance.

Since the 40 Australian coals have appeared in random array in all attempts to correlate precipitator performance with any coal sulphur parameter (see for example Figure 1), it follows that arbitrary selections of the coals can be made displaying a wide variety of relationships between these variables. For example, 22 of the 40 points conform well to a linear relation between precipitator size (at optimum voltage and 15% ash) and log total coal sulphur, the relation being in the popular direction, i.e. low sulphur means larger precipitators (Figure 3a). However, another selection of 18 of the 40 points conforms even better to the opposite relation, i.e. low sulphur means smaller precipitators (Figure 3b). In contrast, a third selection of 20 points forms a narrow horizontal band, meaning that coals with 0.3 - 0.5% sulphur may require a precipitator size anywhere in a range of 4 to 1, i.e. from unusually large to rather small (Figure 3c). On the other hand, 19 points form a narrow vertical band, meaning that the same medium-sized precipitator suffices for all sulphur levels from 0.2 to 2.5% (Figure 3d). It is only when the full assembly of points is used that the futility of seeking a coal sulphur effect stands out (Figure 1).

Because information is not available, the possibility arises that the English data referred to earlier consist essentially of only 5 rather than 24 unrelated coals (blends not being admissible, see Section 6). Clearly, if the true picture is that which prevails in Australia (i.e. no correlation), then there is a chance of a properly-designed experiment being carried out with five chosen coals that happen to conform with a coal sulphur effect. The next section assesses the magnitude of this chance.

5. THE CHANCES OF FINDING A CORRELATION THAT IS NON-EXISTENT

In experimental science there is always a chance of discerning an apparent relation between two variables when none in fact exists. A simulated experiment can show that this chance is not always as remote as intuition would suggest. Consider the following such experiment.

Imagine a practical investigation being undertaken for which five unrelated coals have been selected with sulphur contents at intervals equally-spaced over an acceptably-wide range (for example 0.2 - 4.2%). In the investigation the coals are burned separately in successive trials, each producing a characteristic flyash that is electrostatically precipitated under typical conditions (the exact conditions being irrelevant so long as they are agreed equivalent for all the coals). The five efficiencies of ash collection are then imagined to be measured reliably, the intention being to plot the efficiencies against the corresponding coal sulphur contents and look for a relation between the two.

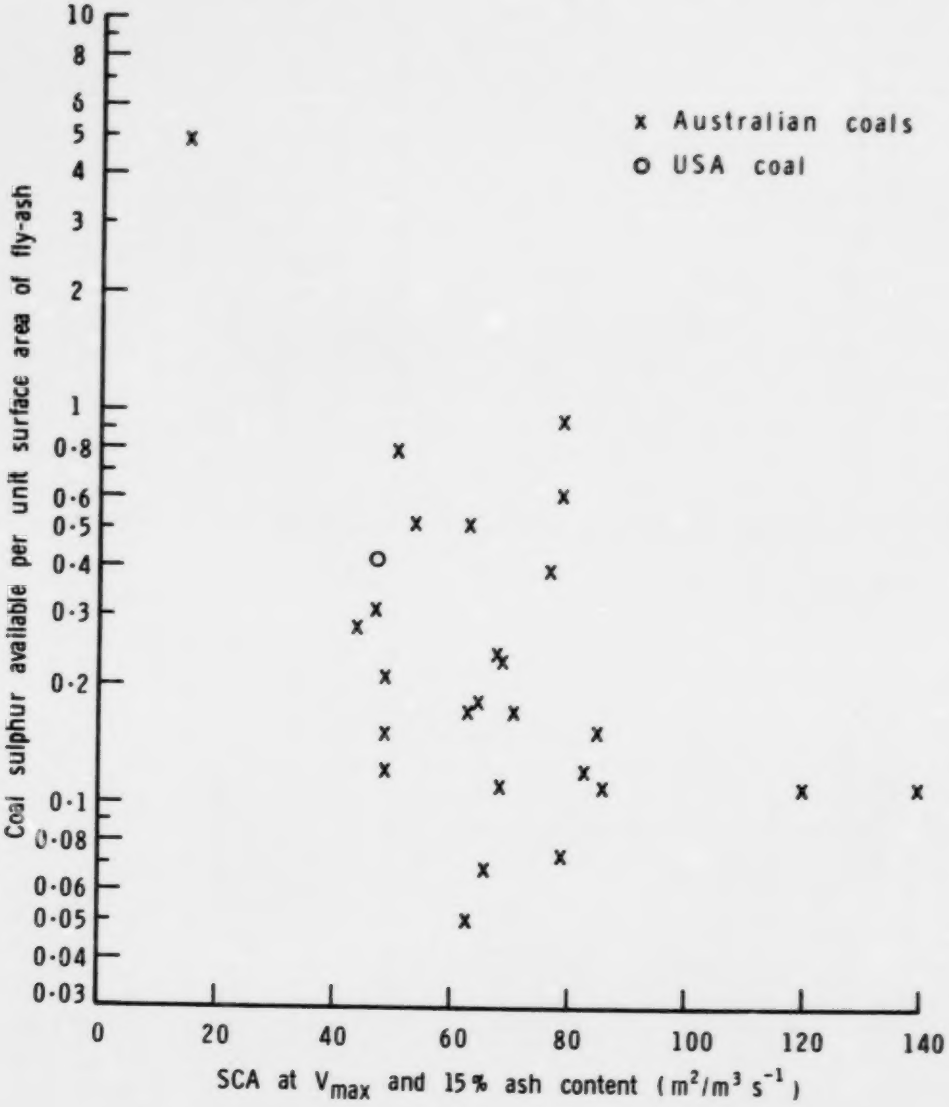

FIGURE 2. PLOT OF A MODIFIED COAL SULPHUR PARAMETER AGAINST SPECIFIC COLLECTING AREA AT 120 °C FOR A FLY-ASH EMISSION OF 0·23 g m^{-3} STP FOR 26 UNRELATED AUSTRALIAN COALS
(Data obtained at maximum voltage and normalized to 15% ash)

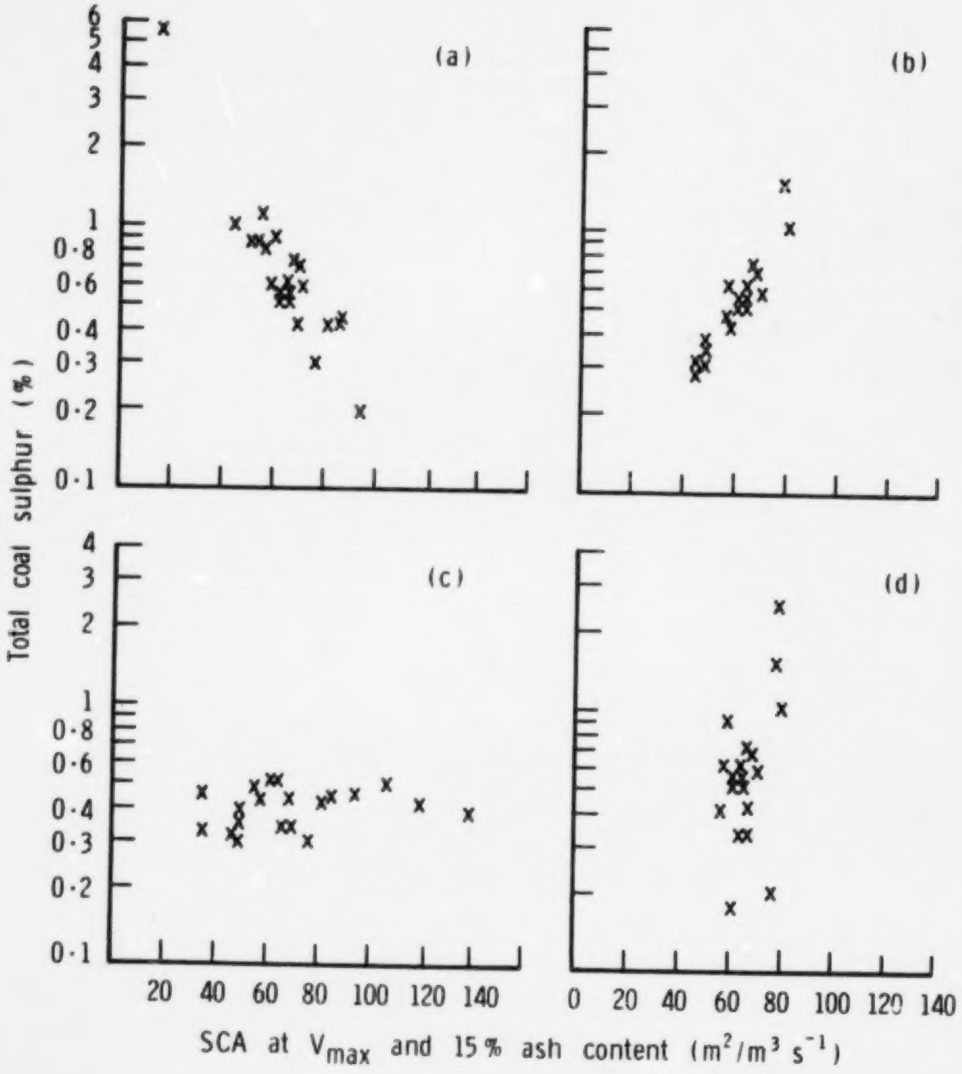

FIGURE 3. ARBITRARY SELECTIONS OF POINTS FROM FIG. 1 SHOWING FALSE CORRELATIONS

Intuitively, most scientists would probably agree that an assembly of five well-spaced points on a graph should suffice to show up a monotonic relation between two variables, although many would prefer to have more than five points to fix such a relation with satisfying precision. Suppose, however, that there is, in fact, no monotonic relation to be found between the two variables; what chance is there of meeting a disposition of the points that leads the observer to conclude (falsely) that the relation does exist?

To answer this question it was supposed that the five efficiencies would be dependent on unspecified variables (not coal sulphur) with levels outside the control of the experimentalist (in precipitation work particle size is one such variable, but the occurrence of uncontrolled variables is common in applied scientific work). These variables would be responsible for such diversity as was observed in the percentage efficiencies, within a range that all would agree reasonable but otherwise unnecessary to specify (say 80.0 - 99.8%, possibly in one hundred equal 0.2% steps). With these imposed (but realistic) conditions, one might as well create the "measured" efficiencies by a random selection process, such as tables of random numbers or picking them out of a hat.

Thus in the simulated experiment a hand calculator was used to select at random the five efficiencies from within a range covering 100 equal steps, and each efficiency was coupled as it was generated to the next sulphur content in order on a repeating list of the five of them compiled beforehand. This procedure was repeated until 96 sets of five points had been assembled, yielding 96 separate graphs. A panel of thirteen post-graduate scientists, active and skilled in experimental research, were then asked to select independently which of the 96 graphs revealed in their judgement a monotonic relation. As might be expected most of the graphs displayed such a wide scatter of the five points that no monotonic relation could be seen by anyone, but some graphs gave more than a hint of a straight line or gentle curve through the points, and a few left the observers in no doubt. Since the scientists' assessments were a matter of personal judgement based on individual experience, unanimity was the exception, but average results of adequate precision were readily obtained. The exercise yielded the following main conclusions :

1. the probability that a monotonic relation in a chosen direction occurred by chance was estimated to be 1 in 11, this estimate being based only on instances where the observer was certain of a relation;

2. if instances were included where the observer suspected but was unsure of a relation, then the probability that a monotonic relation in a chosen direction occurred by chance became 1 in 4.

Paraphrasing the findings of this desktop study, we may say that, in a given 5-point experiment of the kind envisaged, the chance that a competent scientist hopeful of a rising monotonic relation will be happy to see this when there is none at all is 1 in 4; and the chance that an open-minded scientist will be quite sure of it is 1 in 11.

Obviously, when two variables are not cause and effect, something more searching than a 5-point experiment is required to avoid a disturbingly high chance of reporting the opposite of the truth. Indeed to show convincingly that coal sulphur and flyash collection efficiency are unrelated when this is the fact requires much more evidence than to demonstrate they are related when that is the case. This is not the only pitfall for the unwary experimentalist, as the following contrasting example shows.

6. CORRELATIONS TO ORDER FROM GENUINE RESULTS

Figure 4 illustrates a plot of total coal sulphur against the size of precipitator required to achieve the same typical flyash emission. The size has been normalized to 15% ash for each coal in order to eliminate one uncontrolled variable. Each of the four points on the graph is fully experimental, having been obtained from separate combustion and precipitation trials on the technical-scale plant at the authors' laboratory. The results are quite comparable, being obtained at the same temperature and at maximum voltage in every case. Each point is an average based on a number of efficiency tests, and it may be assumed that no additional amount of replication could alter the obvious relation to any significant degree. Although there are only four points (albeit precise ones), the reader may take it that, had any further trials been carried out between the extremes of coal sulphur shown, the additional points would only have confirmed the relation that is there.

Thus, with the reliability of the information in Figure 4 taken for granted, it is indisputable that it shows a quadrupling of the required size of precipitator on passing from 5.6% coal sulphur down to 0.6%; and this behaviour would undoubtedly be reproduced on another occasion if attempted. The authors stress at this point, however, that the results are totally unable to support the popular view that low coal sulphur causes poor flyash precipitation. The reason is important, yet subtle.

The extreme points of Figure 4 (top left and bottom right) originate from two unrelated coals, but the two intermediate points are from separate blends of these two coals. Thus the four coals burnt were related. It is our practical experience that a blend of two coals produces a composite (or mixed) flyash with precipitating properties intermediate between those for the two flyashes separately and pro rata on the proportions of each in the blend. Clearly, the pulverized fragments of each coal burn separately and the flyash particles from each coal solidify too quickly for collisions to merge them into hybrids of different identity. Since precipitation is the sum total of at least as many individual acts of migration as there are flyash particles to collect, the collection efficiency is pro rata on the composition of the coal blend. A graph, therefore, of precipitation properties (observed under comparable conditions) against composition of coal blend is bound to show a smooth monotonic progression between the extremes. Furthermore, any property of the coals or of their flyashes that is also pro rata on the blend will likewise be associated with precipitation properties in the same monotonic fashion.

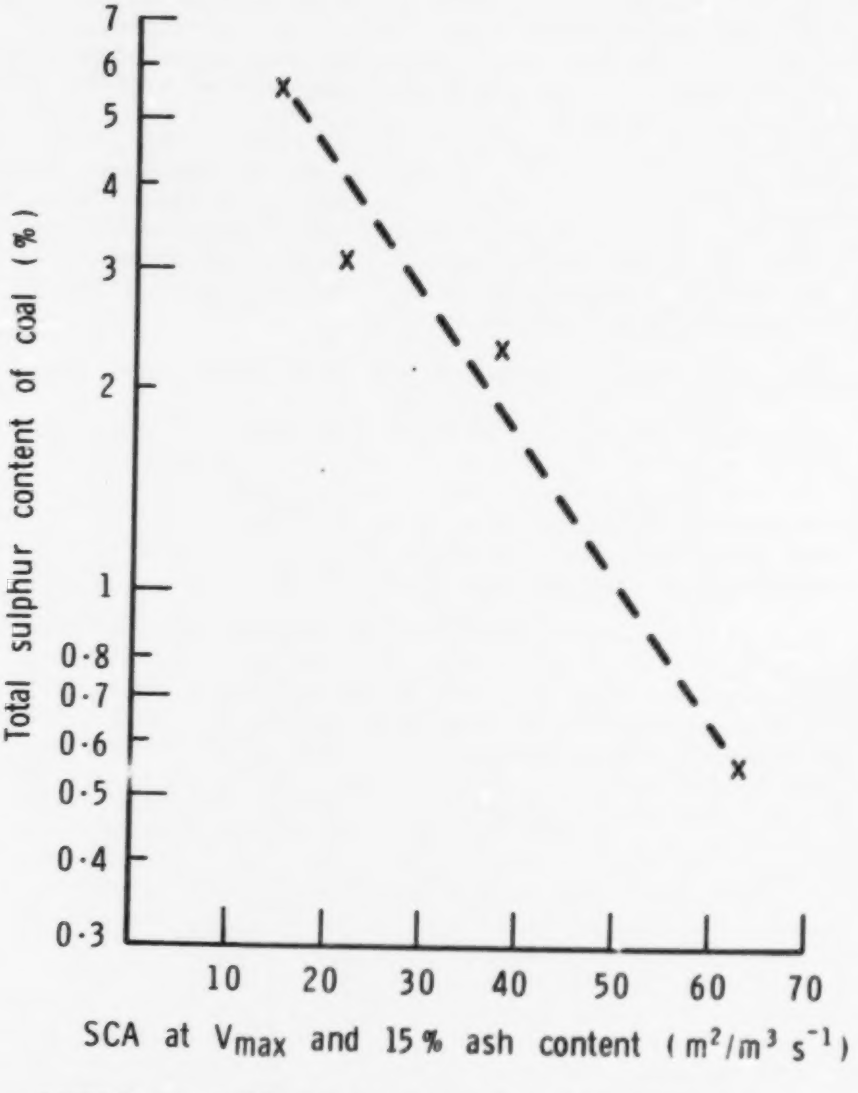

FIGURE 4. PLOT OF TOTAL COAL SULPHUR AGAINST PRECIPITATOR SIZE AT 120 °C SHOWING FALSE CORRELATION DUE TO BLENDING OF TWO COALS

In this category is the sulphur content of the coal blend, and thus Figure 4 shows an inevitable relationship that depends solely on the relative positions of the extreme points of the graph. It is merely a matter of selection of coals in the first place to produce any desired direction of the line displayed in Figure 4 vertical, horizontal, or diagonal with any direction and slope (hence the heading for this section of the paper). Figure 4 is thus quite valueless to show a causal general correlation of coal sulphur with flyash precipitation and it is possible that some published work (including the Ramsdell data and the recent English work) has rather restricted validity because it may be dependent, largely or wholly, on results from coal blends. Certainly, in view of the expense and complex logistics of dust-collection tests in electric utilities, the use of coal blends is a most attractive and economic experimental plan to adopt. It is, however, illusory in the coal sulphur context, as the above example demonstrates.

7. WHY THERE IS NO OVERRIDING EFFECT OF COAL SULPHUR ON FLYASH COLLECTION

There are several reasons why an overriding effect of coal sulphur on flyash collection is not to be expected. The chief reasons requiring comment are (a) the unique surface chemistry of flyash, (b) the existence of alternative sources of surface conduction for flyash, and (c) the masking effect of other variables. In discussing these features it will be seen that some limitations of hot-side precipitation emerge.

The surface chemistry of flyash has recently received considerable clarification through work at the authors' laboratory (Collin (1974)[9]). Most of Collin's work has been carried out on flyash from coals with below 1% sulphur. No exception has yet been found to the rule that the surface of fresh flyash consists essentially of a multimolecular but extremely thin film of aqueous sulphuric acid. Beneath this invisible film is found a layer of calcium sulphate (or exceptionally aluminum sulphate) which separates the acid film from a thin sublayer of calcium hydroxide (or exceptionally alumina). Beneath the sublayer is the glassy aluminosilicate core of the flyash bead. Storage of fresh flyash in air or at elevated temperature promptly removes the outermost acid layer by neutralization and volatilization, and thus the surface properties of the flyash are radically changed. For this reason recovery of accumulated flyash from precipitator hoppers for further collection tests or for later analysis is an unreliable procedure yielding doubtful results. Furthermore, water washing of flyash removes all three layers, exposing the underlying glassy surface, which has quite different electrical properties from those of the fresh product. Hence flyash from lagoons or otherwise washed material is valueless for assessing electrostatic collection if relevance to electric utility application is required.

The meaning of this surface structure of fresh flyash to its electrostatic precipitation is that even low-sulphur coals have a good chance of producing flyash with ample surface electrical conduction at so-called cold-side precipitation temperatures (approximately 110 - 250°C).

Thus, the question whether the particles will receive an adequate sulphuric acid film does not rely in practice on the amount of coal sulphur available, but is more a matter of how long the dispersed flyash has to scavenge sulphur trioxide from a supply in the flue gas that is continually replenished catalytically before the precipitator is reached. That the flyash normally takes up sulphur trioxide rapidly from a sufficient supply is demonstrated by the fact that the flyash is recovered with an acid film present, in spite of a reactive coating of lime (or alumina) and an elevated temperature. If the sulphur trioxide supply were poor or were not being scavenged quickly by the flyash, its surface would not carry any free acid because this would be converted to calcium or aluminium sulphates as soon as it reached the surface.

If, on occasion, at cold-side temperatures, the sulphuric acid film is spread too thinly to be continuous (perhaps as a consequence of poor catalysis or unusually high flyash area), the flyash still need not display excessive resistivity since water absorption by the sublayers (lime/calcium sulphate or alumina/aluminium sulphate) can ensure a complete surface conduction path. At hot-side temperatures (approximately 300 - 450°C) neither sulphuric acid nor water appears on the flyash surface, and conduction must depend on the normal thermal diminution of the resistivity of the glassy core of the flyash particles to acceptable levels. While this so-called volume conduction can be relied upon in many cases at hot-side temperatures, it is dependent on there being no electrically-obstructive coating on the flyash surface. This possibility seems to have been ignored by proponents of hot-side precipitation, since the obstructive film may be provided in the relevant temperature interval by the normal lime (or alumina) coatings on the particles. Instances of back ionization and associated poor precipitation of flyash at hot-side temperatures may find their explanation in such insulating coatings, and this could apply irrespective of the level of sulphur in the coal.

There are numerous variables that influence the precipitation efficiency of flyash at constant temperature and at fixed specific collecting area, including applied voltage, particle size, carrier gas velocity, particle re-entrainment and gas distribution. None of these variables would appear to have any connection with coal sulphur level, and hence if important enough they could mask a presumed effect of coal sulphur. Consider, therefore, the effect on collection efficiency of particle size (expressed as mass median diameter with a mixture of sizes as in flyash). The theoretical effect of particle size is established and enjoys reasonable practical verification (Paulson et al (1976)[10]). With voltage, specific collecting area, and temperature all fixed, the observed migration velocity is directly proportional to the particle size, ignoring mechanical collection efficiency for simplicity. This means, for example, that if a given mean size of particle is associated with a collection efficiency of 90% at a typical operating condition, then doubling the size elevates the efficiency to 99% and tripling the size raises it to 99.9%.

Since it is practical experience (Paulson et al (1976)[10]) to encounter flyashes from different coals that cover nearly a threefold range of mean particle sizes, any specific effect of coal sulphur has to be discerned against an efficiency variation that may range from 90% to over 99% for size reasons alone. In these circumstances it is not realistic to expect to see an overriding effect of coal sulphur on precipitation efficiency of any plausible magnitude. The introduction of the other variables into the argument only serves to strengthen this conclusion.

Bearing in mind that precipitation experts have long recognized the considerable effects on collection efficiency of the several variables listed above, it may well be asked why an overriding influence of coal sulphur has found such wide and prolonged acceptance at cold-side precipitator temperatures. The answer to this question appears to be that low coal sulphur has been considered to render the flyash critically more resistive, so much so that the resulting back ionization is reckoned to neutralize the electrostatic precipitation process itself, thus overriding all other variables. This particular sequence of events now appears to be more of a fear than a fact for the following reasons:

a) there is normally enough sulphur in low-sulphur coal to produce a conducting film of sulphuric acid on flyash at cold-side precipitator temperatures; and discontinuities in the film can be bridged by water interaction with the sublayers of lime or alumina that are present;

b) the effect of applied electric field in reducing the resistivity of highly insulating flyash layers at all practical precipitator temperatures allays losses of collection efficiency that would otherwise occur;

c) if back ionization does take place, it is unlikely to neutralize all collecting areas completely and simultaneously, provided the phasing and intensity of plate rapping are properly selected.

8. CONCLUSION

1. This paper addressed itself to the question: does sulphur in coal dominate flyash collection in electrostatic precipitators? To this we answer: in theory coal sulphur should not be dominant at any typical temperature, and in practice the weight of the evidence confirms it is not.

2. The combined influence of well-established variables produces such large variations in flyash collection efficiency among different coals that any plausible effect of coal sulphur could not be dominating and at most is probably minor.

3. Some coal sulphur is probably vital to efficient precipitation at cold-side temperatures, but sufficient is present in low-sulphur coals to furnish the flyash particles with a conducting film of sulphuric acid, and this alone is normally adequate to prevent resistive impediments to precipitation.

4. When poor flyash collection occurs in hot-side precipitation it is attributable to electrical obstruction by the normal lime or alumina coatings on flyash particles. This situation has no potential for being avoided through the intervention of coal sulphur, as in the case in cold-side precipitation.

5. Experimental tests of whether coal sulphur influences flyash precipitation may give false results either by chance or if coal blends are relied upon.

REFERENCES

1. Ramsdell, R.G. Practical Design Parameters for Hot and Cold Electrostatic Precipitators. Combustion. 45 : 40-43, October 1973.

2. Barrett, A.A. Electrostatic Precipitators - Guidance for Designers and Purchasers. Filtration and Separation. 67-73, Jan/Feb. 1971.

3. Goard, P.R.C., and E.C. Potter. Resistivity in Electrostatic Precipitation - a Re-appraisal. In: Proc. Symp. on "The Changing Technology of Electrostatic Precipitation", Adelaide, South Australia, Nov. 8, 1974. Inst. Fuel (Australian Membership), 1974.

4. White, H.J. Industrial Electrostatic Precipitation. Reading, MA, Addison-Wesley Publishing Co. Inc., 1963, p.297.

5. Potter, E.C. Electrostatic Precipitation Technology : A Different Viewpoint, JAPCA. 28 : 40-46, January 1978.

6. Paulson, C.A.J., E.C. Potter, and K. Ramus. Pilot-Scale Electrostatic Precipitator Tests on Copper Converter Flue Gas. In: Proc. Internat. Clean Air Conf., Brisbane, Australia, May 15-19, 1978. Ann. Arbor, Mich., Ann Arbor Science Publishers Inc., 1978, p.499

7. Sochaczewski, Z.W. The Relevance of New and Stricter Standards for Particulate Emission and Plant Modifications Necessary to Meet Them. CSIRO Conference on Electrostatic Precipitation, Leura, New South Wales, Australia, August 23-24, 1978.

8. Paulson, C.A.J. In: discussion at Symposium on "The Changing Technology of Electrostatic Precipitation", Adelaide, South South Australia, November 8, 1974; separate discussion booklet published by Inst. Fuel (Australian Membership), see pp. 47-48 and diagrams 20-22.

9. Collin, P.J. Some Aspects of the Chemistry of Flyash Surfaces. In : Proc. Symp. on "The Changing Technology of Electrostatic Precipitation", Adelaide, South Australia, November 8, 1974. Inst. Fuel (Australian Membership), 1974.

10. Paulson, C.A.J., R.B. Kahane, and E.C. Potter. Electrostatic Precipitation of Flyash from a Range of Australian Coals. 1976 Conference of the Institute of Fuel (Australian Membership), November 3-5, 1976, Sydney, Australia.

APPENDIX 1

A MODIFIED COAL SULPHUR PARAMETER

Assume all particles of a selected flyash are solid spheres of uniform size equal to the mass median diameter D.

The weight of each particle is $\pi D^3 \rho/6$ when ρ is the density of flyash (assumed constant).

Therefore the number of particles per unit weight of the flyash is $6/\pi D^3 \rho$.

Since the surface area of each particle is πD^2 the total area per unit weight of flyash is $6\pi D^2/\pi D^3 \rho$, i.e. K/D where K is a constant.

If the weight fraction of ash in the coal is A then the area of the flyash per unit weight of coal is KA/D.

If the weight fraction of sulphur in the coal is S then coal sulphur per unit surface area of flyash is SD/KA.

Under circumstances where the available sulphur in coal must be shared equally by all the flyash area, it is preferable to seek a relation between precipitator performance and the parameter SD/A.

ANALYSIS OF THERMAL DECOMPOSITION PRODUCTS OF FLUE GAS CONDITIONING AGENTS

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ABSTRACT

The reactions of two proprietary flue gas conditioning agents used in high temperature applications have been investigated in the laboratory under conditions simulating those in the flue gas train of a coal-burning power plant. The two agents investigated were Apollo Chemical Corporation's Coaltrol LPA-40 and LPA-445. LPA-40 was found to be primarily an aqueous ammonium sulfate solution and LPA-445 an aqueous solution of diammonium hydrogen phosphate. The two predominant types of reactions observed in the study were thermal decomposition and recombination reactions. The primary thermal degradation products of LPA-40 at 650 °C were ammonia and sulfur trioxide. At 160 and 90 °C the decomposition fragments recombined into ammonium sulfate salts. Extensive decomposition of LPA-445 into ammonia and phosphate species was observed at 650 °C, with recombination into ammonium phosphate salts occurring at lower temperatures.

INTRODUCTION

Most of the older electrostatic precipitators used in coal-burning power plants operate at temperatures around 150 °C (300 °F). The recent widespread use of low-sulfur coals in electric power production in order to comply with sulfur dioxide emission regulations has led to difficulty in achieving efficient collection of fly ash in these precipitators. This difficulty is primarily attributable to an increase in the electrical resistivity of the ash, which limits the useful voltage and current that can be maintained in a precipitator.

A common approach that has been taken to improve the collection efficiencies of these precipitators is the injection of chemical additives into the gas stream before it enters the precipitator in order to modify the electrical resistivity of fly ash or to obtain some other beneficial effects on precipitator performance. While chemical conditioning agents have substantially improved precipitator efficiencies in many instances, however, it is conceivable that the injection of chemicals into flue gas may result in the release to the environment of undesirable compounds consisting of the agents, their thermal decomposition products, or their reaction products with components of the flue gas.

We have recently completed a laboratory investigation of the chemical reactions of several flue gas conditioning agents under conditions simulating those in the flue gas train of a coal-burning electric power plant. The primary purposes of the study were to characterize the chemical species resulting from the addition of conditioning agents to the flue gas of a coal-fired power plant and to identify hazardous chemical species originating from the agents that can potentially undergo stack discharge to the environment.

This paper presents the results of our investigations of two proprietary conditioning formulations marketed by the Apollo Chemical Corporation, Coaltrol LPA-40 and Coaltrol LPA-445. The work was funded under EPA Contract 68-02-2200 and was monitored by Dr. Leslie E. Sparks of the Industrial Environmental Research Laboratory at Research Triangle Park, North Carolina.

DESCRIPTION OF THE LABORATORY APPARATUS

For the investigation of the reactions of flue gas conditioning agents, a laboratory bench-scale facility was constructed to simulate the flue gas train in a full-scale coal-burning power plant. The basic flue gas mixture consisted by volume of approximately 76% nitrogen, 12% carbon dioxide, 8% water vapor, and 4% oxygen. This synthetic flue gas was prepared by mixing charcoal-filtered compressed air with nitrogen and carbon dioxide from regulated, compressed gas cylinders and then electrically heating the mixture to a temperature of approximately 650 °C. Water vapor was added to the hot gas mixture by the flash evaporation of metered, gravity-fed liquid water in the heated gas stream. Trace amounts of gaseous sulfur dioxide, nitric oxide, and nitrogen dioxide could be added individually or in various combinations to the hot gas mixture. Typical concentrations of these oxides in the gas stream were, on the volume basis, approximately 600 ppm sulfur dioxide, 1000 ppm nitric oxide, and 100 ppm nitrogen dioxide. The total volume flow rate of the gas mixture was usually maintained at approximately 35 l/min (expressed for 25 °C).

We had originally planned to suspend fly ash in the gas stream to simulate the particulate produced from the combustion of coal. However, the anticipation of technical difficulties associated with resuspending fly ash in the flue gas stream and with interpreting the results of reaction studies in a heterogeneous system led to abandoning the inclusion of fly ash in the system.

The synthetic flue gas mixture was introduced into a series of heated cylinders of quartz, Pyrex, or stainless steel that represented various parts of the flue gas train of a coal-fired power plant extending from a point upstream from the economizer to the outlet of the stack. The principal components of the laboratory train are schematically illustrated in Fig. 1 and are itemized and described briefly below:

- A heated quartz cylinder maintaining a portion of the gas stream at 650 °C, a representative gas temperature in the duct upstream from the economizer.
- A Pyrex heat exchanger representing the economizer.
- A heated Pyrex cylinder maintaining a portion of the gas stream at about 370 °C, a representative gas temperature in the duct between the economizer and the air preheater.
- A Pyrex heat exchanger representing the air preheater.
- A heated Pyrex cylinder maintaining a portion of the gas stream at about 160 °C, representing the temperature in the duct between the air preheater and the electrostatic precipitator.
- A small wire-and-pipe electrostatic precipitator (ESP) maintained at a temperature of about 160 °C.
- A Pyrex heat exchanger simulating cooling near the stack exit.
- A heated Pyrex cylinder maintaining a portion of the gas stream at about 90 °C, a conceivable temperature of the gas stream near the top of the stack.

The dimensions of the cylinders were chosen to provide gas residence times of 2 sec within each cylinder except in the heat exchangers and the ESP. The gas residence time within each of the heat exchangers was a fraction of a second. The gas residence time within the ESP was about 7 sec. Each cylinder enclosing a constant temperature zone was provided with an injection port near its inlet and a sampling port near its outlet.

The ESP was activated in some of the earlier experiments with nonproprietary conditioning agents, but it was not activated in any of the experiments reported in this paper.

CHEMICAL ANALYSIS OF LPA-40 AND LPA-445

Samples of Coaltrol LPA-40 and Coaltrol LPA-445 for use in this investigation were supplied by Apollo Chemical Corporation. Both of these formulations were chemically analyzed so that possible thermal decomposition products of the agents could be postulated. The flue gas stream would be sampled and analyzed for the appropriate chemical species.

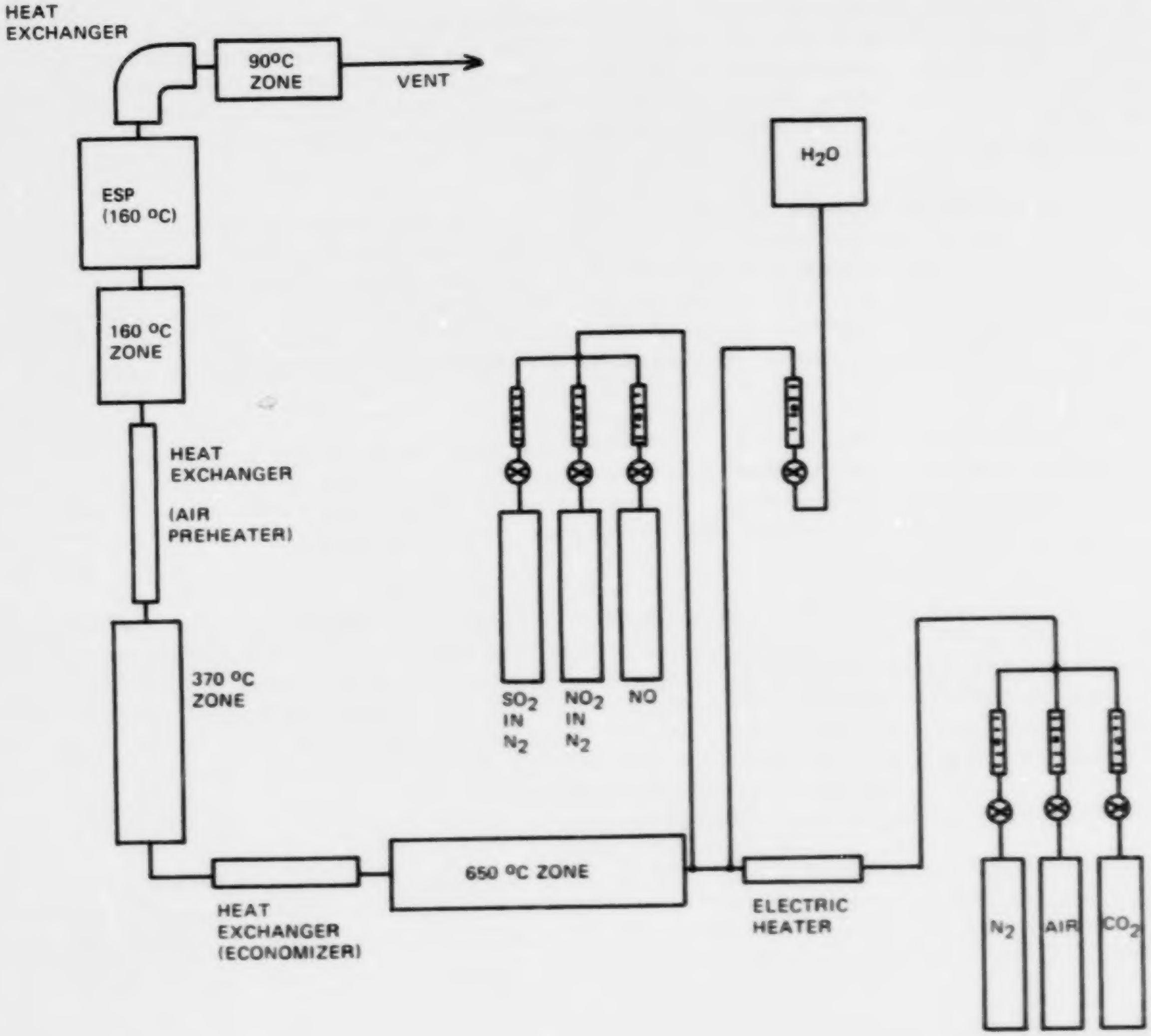

Figure 1. Schematic diagram of flue gas train.

The sample of LPA-40 supplied by Apollo was a light brown solution with a density of 1.27 g/ml and a pH of 3.9. The qualitative identification of the primary components of the formulation was performed by infrared spectroscopy and ion chromatography.[1] The solid material resulting from the evaporation of the solvent from the formulation possessed an infrared spectrum that was identical to that of ammonium sulfate, $(NH_4)_2SO_4$. Analysis of the formulation by ion chromatography revealed that sulfate ion was the only anion that was present in significant amounts.

The LPA-40 formulation was quantitatively analyzed for ammonium ion by the indophenol method[2] and by acid-base titration with sodium hydroxide solution. The sulfate concentration was determined by titration with barium perchlorate solution using Thorin as an indicator.[3] The results of these analyses showed that the LPA-40 formulation consisted of about 40% w/w ammonium sulfate in water.

The brown coloration of our sample of LPA-40 was believed to be due to the presence of ferric ion in the formulation. The LPA-40 solution was analyzed by atomic absorption spectroscopy and was found to contain approximately 0.2% w/w iron. The nature of the iron compound in the formulation was not characterized; but the compound is speculated to be ferric hydroxide, present in the formulation as an impurity in the ammonium sulfate used to prepare the agent.

The sample of LPA-445 was a clear, colorless liquid with a distinct ammoniacal odor. Its density was 1.14 g/ml and its pH approximately 8.2. Mass spectrometric analysis of the solid residue remaining after evaporation of the formulation to dryness indicated that the solid residue was an ammonium phosphate salt.

LPA-445 was identified as an aqueous solution of diammonium hydrogen phosphate, $(NH_4)_2HPO_4$, and the concentration of the solution was determined by analyzing the formulation for ammonium ion by the indophenol method and for orthophosphate ion by ion chromatography and by the vanadomolybdophosphoric acid colorimetric method.[4] The LPA-445 formulation was found to consist of a solution of approximately 24% w/w diammonium hydrogen phosphate in water. Analysis of the formulation by ion chromatography also revealed the presence of trace amounts of sulfate ion (approximately 7.30 µmol/g or 0.08% w/w).

Two separate samples of LPA-445 were used during the investigation of this conditioning agent. Each of the samples was analyzed individually, and the two samples were found to be identical within the experimental limits of error of the chemical methods used in the analyses.

POSTULATED REACTION MECHANISMS

The predominant reaction types expected in the study of both LPA-40 and LPA-445 were thermal decomposition reactions at high temperatures and recombination of the degradation fragments at lower temperatures. At 650 °C the probable decomposition of ammonium sulfate, the major component of LPA-40, was expected to proceed via the following equation:

$$(NH_4)_2SO_4(s) \longrightarrow 2NH_3(g) + H_2O(g) + SO_3(g) \qquad (1)$$

The occurrence of this reaction is consistent with the thermodynamic data of Kelley et al.[5] and Scott and Cattell.[6] In addition, based on the findings of Halstead,[7] nitrogen, nitrogen oxides, and sulfur dioxide were expected as relatively minor products from the thermal decomposition of ammonium sulfate. The recombination of the major thermal decomposition products was expected to proceed by the stepwise reversal of equation 1 with decreasing temperature:

$$SO_3(g) + H_2O(g) \longrightarrow H_2SO_4(g) \tag{2}$$

$$NH_3(g) + H_2SO_4(g) \longrightarrow NH_4HSO_4(l \text{ or } g) \tag{3}$$

$$NH_3(g) + NH_4HSO_4(l \text{ or } g) \longrightarrow (NH_4)_2SO_4(s) \tag{4}$$

We initially expected the major component of LPA-455, diammonium hydrogen phosphate, to dissociate at 650 °C into gaseous ammonia and phosphoric acid. The resultant phosphoric acid was then expected to decompose completely into phosphorus pentoxide (P_2O_5) and water or to polymerize into condensed phosphate species (linear polyphosphates such as pyrophosphate, cyclic metaphosphates, or "infinite chain" metaphosphates).

The thermal decomposition of diammonium hydrogen phosphate was studied by Erdey, Gal, and Liptay[8] by means of thermal gravimetry and differential thermal analysis. This study indicated that diammonium hydrogen phosphate thermally decomposes in a stepwise fashion with several decomposition processes proceeding sequentially as the temperature is raised. These processes are:

$$(NH_4)_2HPO_4(s) \xrightarrow{<150\ ^\circ C} NH_4H_2PO_4(s) + NH_3(g) \tag{5}$$

$$NH_4H_2PO_4(s) \xrightarrow{150\ ^\circ C} NH_4H_2PO_4(l) \tag{6}$$

$$2NH_4H_2PO_4(l) \xrightarrow{>150\ ^\circ C} (NH_4)_2H_2P_2O_7(s) + H_2O(g) \tag{7}$$

$$n(NH_4)_2H_2P_2O_7(s) \xrightarrow{<600\ ^\circ C} 2(NH_4PO_3)_n(s) + nH_2O(g) \tag{8}$$

$$2(NH_4PO_3)_n(s) \xrightarrow{600\text{-}800\ ^\circ C} 2nNH_3(g) + nP_2O_5(g) + nH_2O(g) \tag{9}$$

Thus, on the basis of this study, at 650 °C diammonium hydrogen phosphate was expected to thermally decompose into ammonia, phosphorus pentoxide (which would be analyzed as orthophosphate ion in gas samples removed at 650 °C), and water. As the flue gas stream was cooled from 650 to 90 °C the reaction sequence given in equations 5 through 9 was expected to be reversed. Thus, near the exit of the gas train, the probable recombination products were expected to be diammonium hydrogen phosphate and ammonium dihydrogen phosphate.

The decomposition reactions of both LPA-40 and LPA-445 discussed above were expected to be identical whether or not reactive sulfur and nitrogen oxides were present in the flue gas. However, significant amounts of the ammonia formed during the thermal decomposition of injected LPA-40 and LPA-445 were expected to possibly be destroyed in the 650 °C zone in the presence of added nitrogen oxides in the gas stream due to the reaction of ammonia with nitrogen oxides.

No unusual or highly toxic decomposition or reaction products of measurable concentration were expected to be formed in the gas stream when LPA-40 or LPA-445 were injected. The only highly toxic compound that we could envision possibly being formed in the gas stream was phosphine (PH_3) from the highly unlikely reduction of some phosphorus-containing species during the injection of LPA-445.

INJECTION OF LPA-40 AND LPA-445 INTO THE FLUE GAS

Both of the formulations were introduced into the flue gas stream as aerosols. Dilute, filtered aqueous solutions of LPA-40 and LPA-445 were nebulized at a rate of 0.2 ml/min with a Retec X70/N nebulizer assembly (Burton Division, Cavitron Corporation, Van Nuys, California). The nebulizer was activated with dry nitrogen gas, and the aerosol resulting from the nebulization process was introduced into the 650 °C constant temperature zone through a quartz tube that extended from the outlet of the nebulizer to the center of the flue gas stream. Since Apollo's LPA series of additives are normally used for high temperature application (gas stream temperatures of 590 to 900 °C), both LPA-40 and LPA-445 were injected into the hottest constant temperature zone in our laboratory flue gas train, the 650 °C zone. The rate of injection of LPA-40 was chosen so that the concentration of ammonium sulfate in the flue gas at 650 °C did not exceed the upper limit specified by Apollo, 41 μg/l.[9,10] The measured concentrations of ammonium sulfate injected into the flue gas stream over the course of the study ranged from 9 to 41 μg/l at 650 °C. No information was found on the concentration of diammonium hydrogen phosphate in the flue gas recommended by Apollo. The rate of injection of LPA-445 was thus somewhat arbitrary and ranged from approximately 14 to 67 μg/l at 650 °C during the first half of the study of LPA-445. During the second half of the study, however, the nebulizer began malfunctioning, and the injection rates ranged from only 4 to 26 μg/l.

The average injection rates of ammonium sulfate and diammonium hydrogen phosphate were determined by chemically analyzing the solutions in the nebulizer before and after a series of experiments. The solutions of LPA-40 were analyzed for ammonium ion and sulfate ion, and the LPA-445 solutions were analyzed for ammonium ion and phosphate ion. The injection rates were calculated from the differences in the amounts of ammonium ion and sulfate or phosphate ion in the nebulizer before and after the nebulization period. These analyses indicated that in many experiments with LPA-40 as much as 25% more ammonium ion was injected into the gas stream than was sulfate (based on the ratio of equivalents lost from the nebulizer). In the experiments with LPA-445, a 25% excess of ammonium ion relative to phosphate ion (again on an equivalent basis) was apparently nebulized into the gas stream when the nebulizer was functioning properly. During the later experiments, when the nebulizer was not functioning properly, the average excess of ammonia over phosphate averaged 90%. The apparent origin of the excess ammonia during the nebulization of LPA-40 was the decomposition of a residue of ammonium sulfate that collected in the quartz tube of the nebulizer at high injection rates. The excess ammonia, apparently injected during the nebulization of LPA-445, can be partially explained by the appreciable vapor pressure of ammonia that is present over solutions of diammonium hydrogen phosphate, even at room temperature, and by the decomposition of solid ammonium dihydrogen phosphate that collected in the quartz tube of the nebulizer. However, these cannot completely accout for the large excess of injected ammonia during the period of malfunctioning of the nebulizer, and no satisfactory explanation could be found.

SAMPLING AND ANALYTICAL METHODS

During the investigations of LPA-40 and LPA-445, the flue gas was sampled and analyzed for a variety of substances. In both studies the gas stream was analyzed for background sulfur dioxide, sulfur trioxide, nitric oxide, and nitrogen dioxide. In the investigation of LPA-40, the gas stream was specifically analyzed for ammonia, ammonium ion, sulfate ion, sulfite ion, nitrate ion, nitrite ion, and iron. In the investigation of LPA-445, the gas stream was specifically analyzed for ammonia, ammonium ion, orthophosphate ion, condensed phosphate species (pyrophosphates, metaphosphates, etc.), and phosphine. The selection of these compounds for analysis was based on the anticipated thermal decomposition reactions of the conditioning agents and the expected chemical reactions of the agents or their degradation products with various components of the flue gas stream.

Sulfur trioxide was determined by sampling the flue gas through a controlled condensation coil[11,12] and by subsequently measuring the collected sulfate by the barium perchlorate-Thorin titration method or by ion chromatography. Sulfur dioxide was collected downstream from the coil in a bubbler containing 3% hydrogen peroxide, and the resulting sulfate was determined by titration of the bubbler solution with 0.1 N sodium hydroxide to the bromphenol blue endpoint or by analyzing the solution for sulfate by ion chromatography.

In the absence of added nitrogen oxides to the gas stream, nitrogen dioxide was determined by the Greiss-Saltzman procedure;[13] nitric oxide was first oxidized to nitrogen dioxide on firebrick impregnated with chromium trioxide and then analyzed by the Greiss-Saltzman method. In the presence of added nitrogen oxides, the phenoldisulfonic acid method[14] was used to determine the sum of nitric oxide and nitrogen dioxide concentrations (as nitrate ion), and the Greiss-Saltzman method was used to determine the nitrogen dioxide concentration. The concentration of nitric oxide was determined by difference.

In the investigation of LPA-40, ammonia was absorbed from the flue gas in bubblers containing 0.1 N sulfuric acid; the resulting ammonium ion was then determined by the indophenol colorimetric procedure. Particulate material from the flue gas was collected ahead of the bubblers on heated quartz wool plugs at 650 °C and on heated Teflon filters at 160 and 90 °C. Exposed filters and plugs were usually washed with distilled, deionized water. The washes were analyzed for ammonium ion by the indophenol method and for sulfate, sulfite, nitrate, and nitrite by ion chromatography. In some experiments, exposed filters were washed with tetrachloromercurate solution, and sulfite was determined by the West-Gaeke method.[15] In other experiments, iron was determined by atomic absorption spectroscopy in either water washes or hot hydrochloric acid washes of the quartz wool plugs.

In the investigation of LPA-445, the gas stream was usually sampled through a particulate filter (either a quartz wool plug at 650 or 370 °C or a fine porosity Teflon disc at 160 or 90 °C) and then through a bubbler of 0.1 N sulfuric acid. The material collected on a filter or in the bubbler was analyzed for ammonium ion, orthophosphate ion, and condensed phosphate species. In a few experiments the gas stream was sampled into a bubbler of sodium bicarbonate-sodium carbonate buffer solution, and the solution was subsequently analyzed by ion chromatography. Ammonium ion was determined by the indophenol method. Orthophosphate and condensed phosphate ions were determined colorimetrically, either by the vanadomolybdophosphoric acid method or by the stannous chloride method.[16] In both methods, orthophosphate ion was determined directly, whereas condensed phosphate ions were first hydrolyzed by boiling in a dilute acid solution and then determined colorimetrically as orthophosphate ion.

In one set of experiments with LPA-445 the gas stream was sampled through a bubbler containing silver diethyldithiocarbamate reagent and analyzed colorimetrically for phosphine.[17]

VARIATION OF EXPERIMENTAL PARAMETERS

The experimental parameters that were varied in these investigations included the composition of the flue gas into which LPA-40 and LPA-445 were added and the temperature of removal of gas samples to be analyzed. The specific combinations of experimental conditions that were employed are shown in Table 1. In the investigation of each agent, the first series of experiments was conducted with a simplified flue gas mixture containing no added oxides of sulfur or nitrogen. In the later series of experiments, the reactive oxides of sulfur and nitrogen were added.

Table 1. EXPERIMENTAL CONDITIONS USED IN THE INVESTIGATIONS OF LPA-40 AND LPA-445

Gas composition	Injection temperature, °C	Sampling temperature, °C
No added SO_x or NO_x	650	650, 370 (LPA-445 only), 160, and 90
600 ppm SO_2 added	650	650 (LPA-445 only)
600 ppm SO_2, 1000 ppm NO, and 100 ppm NO_2 added	650	650, 160, and 90 (LPA-40); 160 and 90 (LPA-445)

As previously discussed, both LPA-40 and LPA-445 were added to the gas stream at 650 °C in all of the experiments. In the investigation of LPA-40, the flue gas was usually removed near the outlet of the 650 °C zone into a sampling manifold. In some experiments the sampling manifold was maintained as hot as possible (approximately 500 °C) in order to study the thermal degradation of the conditioning agent, and in other experiments the flue gas was allowed to cool rapidly to 160 or 90 °C in the sampling train in order to study the recombination reactions of the decomposed conditioning agent. The purpose of this sampling procedure was to minimize the wall losses that would have occurred in the flue gas train if the gas stream had been sampled at the outlets of the 160 and 90 °C constant temperature zones. In the investigation of LPA-445, the sampling manifold was not used due to gas flow metering problems encountered in the use of the manifold in the investigation of LPA-40. Rather, the flue gas was sampled directly from the outlet of the 650 °C zone in the thermal decomposition studies and from the outlets of the 370, 160, or 90 °C zones in the recombination studies.

EXPERIMENTAL RESULTS OF THE INVESTIGATION OF LPA-40

Thermal Decomposition Studies

Typical results of the thermal decomposition studies of LPA-40 are given in Table 2. The primary thermal degradation products of LPA-40, at 650 °C in flue gas containing no added sulfur or nitrogen oxides, were sulfur trioxide, sulfur dioxide, and ammonia. The sulfur oxides recovered were approximately 90% sulfur trioxide and 10% sulfur dioxide. Microgram quantities of a solid iron compound were also found, but the iron compound was not further characterized. Nitrogen or nitrogen oxides should also have been produced along with sulfur dioxide from the oxidation of ammonia by sulfur trioxide. Because of the large background levels of nitrogen in the flue gas, however, measurement of the trace amounts of nitrogen produced by this reaction was not possible. Nitrogen oxides were found at levels no higher than the background concentrations of approximately 10 ppb.

In one set of experiments, instead of injecting LPA-40, an aqueous solution of ordinary ammonium sulfate was injected into flue gas containing no added sulfur or nitrogen oxides. The primary thermal degradation products of ammonium sulfate found were the same as those of LPA-40 at 650 °C—ammonia, sulfur trioxide, and sulfur dioxide. The sulfur oxides recovered consisted of about 95% sulfur trioxide and 5% sulfur dioxide. There was no indication that the relative amount of sulfur dioxide changed significantly as the result of the absence of the iron compound found in LPA-40.

The primary thermal decomposition products of LPA-40 in flue gas containing added sulfur and nitrogen oxides were sulfur trioxide and ammonia, the same principal degradation products that were found in the absence of reactive gases in the flue gas stream. Because of the large background concentrations of sulfur dioxide that were added to the gas stream in these experiments, however, the small amounts of sulfur dioxide produced during the thermal degradation of LPA-40 that were observed in the absence of reactive gases could not be detected.

Recombination Studies

No Oxides of Sulfur or Nitrogen Added to Flue Gas. The averaged results of the recombination studies of LPA-40 in the absence of added reactive oxides in the flue gas are given in Table 3. When the gas stream was sampled at

Table 2. DETERMINATION OF THERMAL DECOMPOSITION PRODUCTS OF LPA-40 AT 650 °C

	Concentration, meq/l x 10,000*					
	Observed				Injected	
Gas composition	SO_3	SO_2	Total SO_x	NH_3	SO_4^{-2}	NH_4^+
Without added SO_2 or NO_x	4.97	0.56	5.53	4.44	6.11	6.11†
Without added SO_2 or NO_x‡	5.54	0.22	5.76	5.01	7.81	7.53
With 600 ppm SO_2 and 1100 ppm NO_x added	3.43	-	-	3.21	7.85	7.85†

* Expressed for 25 °C. To convert the concentrations to parts per million (gas by volume) multiply the SO_3 and SO_2 concentrations by 1.22 and the NH_3 and NH_4^+ concentrations by 2.44.

† Not determined independently. Based on SO_4^{-2} lost from the nebulizer.

‡ An ammonium sulfate solution was injected instead of LPA-40 in this experiment.

160 °C, the primary product found on the particle filters appeared to be ammonium bisulfate, NH_4HSO_4. Evidence of lesser amounts of ammonium sulfate was also found by analysis of the filters, but the predominance of the bisulfate salt was indicated by the low ratios of ammonium ion concentration to the anion concentration. These ratios are listed in Table 4. Expressed in equivalents, the average ratio was 0.59. This corresponded to mole fractions of 0.83 for ammonium bisulfate and 0.17 for ammonium sulfate in the filter catch. An average of about 4% of the total sulfur species recovered was sulfur trioxide (or sulfuric acid vapor), and about 4% was recovered as sulfur dioxide. Ammonia was the only nitrogen compound found at significant concentrations. Nitrogen oxides were not above the background levels.

When the gas stream was sampled at 90 °C, the primary recombination product found appeared to be ammonium sulfate. The average ratio of ammonium ion concentration to anion concentration expressed in terms of equivalents was 0.89. This corresponded to mole fractions of 0.76 for ammonium sulfate and 0.24 for ammonium bisulfate in the filter catch. Sulfur trioxide (or sulfuric acid vapor) was found to be present at concentrations representing 0.5 to 0.8% of the sulfur compounds, while sulfur dioxide represented from 4 to 6%. Since no sulfuric acid should exist as vapor at 90 °C, the sulfuric acid found must have occurred as fine particles of condensed liquid that slipped through the filter. As above, ammonia was the only nitrogen compound found in significant concentrations.

When ordinary ammonium sulfate was injected into the flue gas instead of LPA-40, the predominant recombination product found at 160 °C was apparently ammonium bisulfate; at 90 °C the main product appeared to be ammonium sulfate,

Table 3. RESULTS OF THE RECOMBINATION STUDIES OF LPA-40 AND AMMONIUM SULFATE IN FLUE GAS CONTAINING NO ADDED OXIDES OF SULFUR OR NITROGEN

		Concentration, meq/l x 10,000*					
		Observed (averaged values)					
Agent injected	Sampling temp., °C	HSO_4^- or SO_4^{-2}	SO_3	SO_2	Total sulfur species	SO_4^{-2} injected	Recovery, %
LPA-40	160	7.31	0.29	0.31	7.91	13.81	57
	90	14.80	0.11	0.73	15.64	19.08	82
$(NH_4)_2SO_4$	160	5.29	0.06	0.14	5.49	7.45	74
	90	5.35	0.06	0.14	5.55	7.45	74
		NH_4^+	NH_3		Total nitrogen species	NH_4^+ injected	
LPA-40	160	4.28	5.89		10.17	13.63	75
	90	13.07	5.52		18.59	19.30	96
$(NH_4)_2SO_4$	160	3.06	-		-	8.01	-
	90	4.53	-		-	8.01	-

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* Expressed for 25 °C. To convert the concentrations to parts per million on a hypothetical volume basis, multiply the concentrations of the sulfur species by 1.22 and the concentrations of NH_4^+ and NH_3 by 2.44.

Table 4. ANALYSIS OF THE RECOMBINATION PRODUCTS OF LPA-40 AND AMMONIUM SULFATE IN FLUE GAS CONTAINING NO ADDED OXIDES OF SULFUR OR NITROGEN

Agent injected	Sampling temp., °C	$\left(\frac{[NH_4^+]}{[HSO_4^-] \text{ or } [SO_4^{-2}]}\right)$ found on filter	Mole fraction NH_4HSO_4	Mole fraction $(NH_4)_2SO_4$
LPA-40	160	0.59	0.83	0.17
	90	0.89	0.24	0.76
$(NH_4)_2SO_4$	160	0.58	0.84	0.16
	90	0.85	0.30	0.70

as during the injection of LPA-40. The predominance of one sulfate salt over the other was indicated by the ratios of ammonium ion concentrations to the sulfate and bisulfate concentrations (Table 4). At 160 °C the average ratio expressed in terms of equivalents was 0.58, which corresponds to mole fractions of 0.84 for ammonium bisulfate and 0.16 for ammonium sulfate. At 90 °C the average was 0.85, which corresponds to mole fractions of 0.70 for ammonium sulfate and 0.30 for ammonium bisulfate.

Sulfur and Nitrogen Oxides Added to Flue Gas. The averaged results of the recombination studies of LPA-40 in flue gas containing added oxides of sulfur and nitrogen are given in Table 5. The predominant recombination products found at 160 and 90 °C were ammonium sulfate salts. However, uncertainties in the data did not permit a definite conclusion to be drawn about the distribution of the recombination products between ammonium sulfate and ammonium bisulfate. The data obtained in these experiments were based on only a few determinations, had a large scatter, and gave poor mass balances. At 160 °C the ratio of ammonium ion concentration to anion concentration (each expressed in meq/l) was found to range from 0.85 in one experiment (which would indicate a predominance of ammonium sulfate) to 0.21 in another (which could indicate the occurrence of ammonium bisulfate in an excess of sulfuric acid). At 90 °C the ratio ranged from 0.51 to 0.06. With the exception of one value of 0.41, which corresponds to mole fractions of 0.98 for ammonium bisulfate and 0.02 for ammonium sulfate, these low ratios indicate an excess of sulfuric acid over any ammonium salt present. Any sulfate salt initially formed would have been converted to the bisulfate salt by the excess acid.

Table 5. RESULTS OF THE RECOMBINATION STUDIES OF LPA-40 IN FLUE GAS CONTAINING ADDED OXIDES OF SULFUR AND NITROGEN

	Concentration, meq/l x 10,000*				
	Observed (averaged values)				
Sampling temp., °C	HSO_4^- or SO_4^{-2}	SO_3	Total sulfur species	SO_4^{-2} injected†	Recovery, %
160	2.08	0.41	2.49	5.12	49
90	6.80	0.37	7.17	9.62	75
	NH_4^+	NH_3	Total nitrogen species	NH_4^+ injected†	
160	2.02	0.22	2.24	5.12	44
90	1.93	0.23	2.16	9.62	22

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* Expressed for 25 °C. To convert the concentrations to parts per million on a hypothetical volume basis, multiply the concentrations of the sulfur species by 1.22 and the concentrations of NH_4^+ and NH_3 by 2.44.

† Based on SO_4^{-2} lost from nebulizer.

The only chemical species found at significant levels in any of the experiments with added sulfur and nitrogen oxides in the gas stream were ammonium and sulfate ions, sulfur trioxide, and ammonia. Only negligible amounts of nitrite, nitrate, and sulfite ions could be detected in any of the filter washes analyzed by ion chromatography. And because of the high background levels of nitric oxide, nitrogen dioxide, and sulfur dioxide, the small quantities of these oxides that could possibly be formed in these experiments could not be determined.

In most of the experiments with added nitrogen oxides present in the gas mixture, the concentrations of ammonia and ammonium ion recovered from the gas stream were significantly less than the injected concentrations of ammonium ion into the flue gas. This observation is consistent with the finding obtained in earlier studies with ammonia during these investigations that extensive reaction occurs between nitrogen oxides and ammonia in the flue gas train at 650 °C.

EXPERIMENTAL RESULTS OF THE INVESTIGATION OF LPA-445

Injection of LPA-445 into Flue Gas Containing No Added Oxides of Sulfur or Nitrogen

The experimental results of the study of LPA-445 in flue gas containing no added oxides of sulfur or nitrogen are given in Tables 6 and 7. Table 6 compares the total amounts of ammonium and phosphate ions that were collected with the amounts injected. Table 7 gives the quantities of ammonium, orthophosphate, and condensed phosphate ions found on the particulate filters and in the bubbler solutions.

Thermal Decomposition Studies. The thermal degradation products of LPA-445 found at 650 °C on the filters and in the bubblers in flue gas containing no added sulfur or nitrogen oxides were ammonium ion, orthophosphate ion, and condensed phosphate ions. Table 6 shows that, on the average, 88% of the injected ammonium ion was recovered at 650 °C whereas only 52% of the injected phosphate ion was recovered. This difference in recoveries strongly suggests that when LPA-445 was injected into the gas stream at 650 °C diammonium hydrogen phosphate decomposed extensively into gaseous ammonia and particulate phosphate species. The low recovery of the phosphate species can be attributed chiefly to wall losses of phosphate particles due to either impingement and adsorption or to settling out of the particles.

From Table 7 it can be seen that about 90% of the recovered ammonium ions was collected in the bubbler, a result also indicating that extensive decomposition of the diammonium phosphate to ammonia gas occurred. For phosphate ions, roughly 50% was found either on the filter or in the bubbler. This result suggests that extensive volatilization of phosphate, perhaps to phosphorus pentoxide, also occurred. On the other hand, the presence of a significant fraction of the phosphate on the filter suggests that part of the phosphate remained as particulate. The mole ratio of ammonium ion to total phosphate on the filter was approximately 0.9. This ratio suggests that the filter may have collected an ammonium phosphate solid with a mole ratio of ammonium ion to phosphate of 1:1. The thermal stabilities of ammonium

Table 6. RECOVERY OF DECOMPOSITION AND RECOMBINATION PRODUCTS OF LPA-445 IN FLUE GAS CONTAINING NO ADDED OXIDES OF SULFUR OR NITROGEN

Sampling temp., °C	Concentration, μmol/l*				Recovery, %	
	Injected†		Observed			
	NH_4^+	Total PO_4^{-3}	NH_4^+	Total PO_4^{-3}	NH_4^+	Total PO_4^{-3}
650	1.666	0.660	1.462	0.344	88	52
370	2.838	1.363	2.173	0.772	77	57
160	1.949	0.706	1.131	0.111	58	16
90	2.271	0.879	0.921	0.119	41	14

* Expressed for 25 °C. To convert to parts per million on a hypothetical volume basis, multiply by 24.4.

† Based on NH_4^+ and PO_4^{-3} lost from nebulizer.

Table 7. DISTRIBUTION OF DECOMPOSITION AND RECOMBINATION PRODUCTS OF LPA-445 IN FLUE GAS CONTAINING NO ADDED OXIDES OF SULFUR OR NITROGEN

Sampling temp., °C	Concentration, μmol/l*					
	Collected on filter			Collected in bubbler		
	NH_4^+	Ortho-PO_4^{-3}	Condensed PO_4^{-3}	NH_4^+	Ortho-PO_4^{-3}	Condensed PO_4^{-3}
650	0.124	0.123	0.041	1.338	0.156	0.025
370	0.267	0.393	0.148	1.906	0.188	0.042
160	0.102	0.068	0.029	1.028	0.002	0.011
90	0.127	0.087	0.013	0.794	0.004	0.016

* Expressed for 25 °C. To convert to parts per million on a hypothetical volume basis, multiply by 24.4.

orthophosphates, however, make the existence of an ammonium phosphate solid appear improbable at 650 °C. Perhaps gaseous compounds were merely adsorbed on the quartz wool in a ratio suggesting a stoichiometric compound.

The decomposition studies at 650 °C also led to the following observations:

- Approximately 25% of the original orthophosphate was converted to condensed phosphate (see Table 7).

- Negligible quantities of ammonia were oxidized to nitrogen oxides. The total concentration of nitrogen oxides was about 1% of the concentration of ammonium ion collected on the filter and in the bubbler.

Recombination Studies. At 370, 160, and 90 °C, ammonium ion, orthophosphate ion, condensed phosphate ion, and traces of nitrogen oxides were found in the gas stream. These were the same species found in the flue gas sampled at 650 °C. As shown in Table 6, the recovery of ammonium ion was greater than the recovery of total phosphate ion at each of the three collection temperatures. The recovery of ammonium ion averaged 77, 58, and 41%, respectively, at 370, 160, and 90 °C. The recovery of total phosphate species averaged 57, 16, and 14% at the same temperatures. The greater recovery of ammonium ion relative to phosphate ion at all collection temperatures (see Table 6) seems to indicate, as discussed previously, that the collected ammonium ion originated from a gaseous species (ammonia) in the flue gas stream and that the collected phosphate ions originated from particulate phosphate species. However, the data in Table 6 also show a general decrease in the recoveries of both ammonium ion and phosphate ion, as the physical location of the sampling point was further removed from the conditioning agent injection point. The decreasing recoveries of phosphate ions can be attributed to wall losses of particulate phosphate species, but wall losses alone would be inadequate to explain decreasing recoveries of gaseous ammonia. Rather, the trend of decreasing recoveries of ammonium ion indicates that recombination of ammonia with particulate phosphate species occurred in the gas stream at the lower temperatures. The decreasing recoveries of ammonium ion at the lower temperatures can thus be partially attributed to wall losses of particulate ammonium phosphate salts.

On the average nearly 90% of the ammonium ion collected at each temperature was found in the bubbler solution. This indicates that the source of the ammonium ion collected in the bubbler was gaseous ammonia. This ammonia gas presumably originated from two separate sources: (1) the original decomposition of diammonium hydrogen phosphate, or (2) the injection of excess ammonia from the nebulizer.

At 370 °C, approximately 70% of the total collected phosphate was found on the particle filter. This percentage increased to approximately 85% at 160 and 90 °C. These results indicate that as the temperature was lowered the extent of recombination of the original decomposition products into solid ammonium phosphate salts increased significantly. At all of the sampling temperatures, approximately 75% of the phosphate ions collected on the particle filters were orthophosphate ions.

The mole ratios of ammonium ion to orthophosphate ion and ammonium ion to total phosphate ion collected on the Teflon filters were approximately the same at both 90 and 160 °C, 1.0:1.0 and 1.0:1.5, respectively. This indicated that the same recombination product was present at both temperatures. Thermodynamically, ammonium dihydrogen phosphate appeared to be the most probable recombination product at both 90 and 160 °C. However, based on the amounts of phosphate ion found at 90 and 160 °C and the equilibrium dissociation pressures of monoammonium and diammonium phosphate at these temperatures, the only species that would be expected to be found on the particulate filter at either of these temperatures would be monoammonium phosphate at 90 °C—i.e., $NH_4H_2PO_4$.

The assertion that the only stable ammonium phosphate species at either 160 or 90 °C should be monoammonium dihydrogen phosphate at 90 °C is explained as follows. The weight of phosphate ion collected on the particulate filter at 90 °C corresponded to an average gas stream concentration of 3.0 ppm of phosphate as a hypothetical vapor. At 160 °C the weight collected corresponded to an average of 4.0 ppm of phosphate. The dissociation pressures of diammonium hydrogen phosphate at 90 and 160 °C are 4.57 and 257 mmHg, respectively.[18] These dissociation pressures correspond to 6,000 and 340,000 ppm of NH_3 at 90 and 160 °C, respectively. Thus, the amounts of phosphate collected at 90 and 160 °C were totally insufficient to produce the ammonia concentrations that would be in equilibrium with diammonium hydrogen phosphate.

The dissociation pressure of monoammonium dihydrogen phosphate is 0.05 mmHg (66 ppm) at 125 °C.[19] The value is not known at 90 °C, but it is probably low enough to be consistent with the occurrence of the monoammonium salt at 90 °C. The dissociation pressure at 160 °C is also unknown, but it is certainly too high to be consistent with the occurrence of the monoammonium salt at 160 °C. But since the experimental data indicate that the same recombination product was present at both 90 and 160 °C, perhaps the monoammonium phosphate salt was stabilized at 160 °C by some process such as adsorption on the particulate filter.

Injection of LPA-445 into Flue Gas Containing Added Oxides of Sulfur and Nitrogen

The experimental results of the study of LPA-445 in flue gas containing only added sulfur dioxide or both sulfur dioxide and nitrogen oxides are given in Tables 8 and 9. These tables are analogous to Tables 6 and 7. Table 8 compares the total amounts of ammonium and phosphate ions that were collected with the amounts injected. Table 9 shows the quantities of ammonium, orthophosphate, and condensed phosphate ions found on the filters and in the bubblers.

Thermal Decomposition Studies. When approximately 600 ppm of sulfur dioxide was added to the flue gas, ammonium ion, orthophosphate ion, and condensed phosphate ion were again collected on filters and in bubblers at 650 °C. Table 8 shows that, on the average, approximately 63% of the injected ammonium ion and 55% of the injected phosphate ion were recovered at 650 °C, the remainder of the injected ions presumably being lost on the walls of the 650 °C reaction zone and sampling port. Table 9 shows that about 86% of the ammonium ions was collected in the bubbler, whereas 75% of the total phosphate ions was found on the filter and 25% in the bubbler. These results indicate

Table 8. RECOVERY OF DECOMPOSITION AND RECOMBINATION PRODUCTS OF LPA-445 IN FLUE GAS CONTAINING ADDED OXIDES OF SULFUR AND NITROGEN

Sampling temp., °C	Concentration, μmol/l*				Recovery, %	
	Injected†		Observed			
	NH_4^+	Total PO_4^{-3}	NH_4^+	Total PO_4^{-3}	NH_4^+	Total PO_4^{-3}
650 (SO_2 only)	0.625	0.231	0.397	0.127	63	55
160 (SO_2 only)	0.893	0.133	0.297	0.020	34	15
160 (SO_2 and NO_x)	1.096	0.230	0.140	0.017	13	8
90 (SO_2 and NO_x)	1.231	0.392	0.078	0.025	7	6

* Expressed for 25 °C. To convert to parts per million on a hypothetical volume basis, multiply by 24.4.

† Based on NH_4^+ and PO_4^{-3} lost from nebulizer.

Table 9. DISTRIBUTION OF DECOMPOSITION AND RECOMBINATION PRODUCTS OF LPA-445 IN FLUE GAS CONTAINING ADDED OXIDES OF SULFUR AND NITROGEN

Sampling temp., °C	Concentration, μmol/l*					
	Collected on filter			Collected in bubbler		
	NH_4^+	Ortho-PO_4^{-3}	Condensed PO_4^{-3}	NH_4^+	Ortho-PO_4^{-3}	Condensed PO_4^{-3}
650 (SO_2 only)	0.057	0.065	0.030	0.340	0.028	0.004
160 (SO_2 only)	0.153	0.011	0.003	0.143	0.002	0.004
160 (SO_2 and NO_x)	0.032	0.010	-	0.108	0.004	0.004
90 (SO_2 and NO_x)	0.027	0.018	0.001	0.051	0.004	0.002

* Expressed for 25 °C. To convert to parts per million on a hypothetical volume basis, multiply by 24.4.

that at 650 °C the diammonium hydrogen phosphate in LPA-445 decomposed primarily into gaseous ammonia and particulate phosphate species, with some volatilization of phosphate, probably to phosphorus pentoxide, also occurring.

Although these results were qualitatively very similar to the results obtained in the absence of added reactive gases, there were, however, some quantitative differences. Much larger recoveries of ammonium ion were found in the absence of reactive gases (approximately 88%) than in the presence of added sulfur dioxide, and a larger fraction of the phosphate species was found in the bubblers (approximately 50%). These results indicate that more extensive thermal decomposition of diammonium hydrogen phosphate and more extensive volatilization of phosphate ion occurred in the absence of reactive gases than with sulfur dioxide added to the gas stream. No satisfactory explanation for this observation, however, can be offered.

Recombination Studies. With both sulfur oxides and nitrogen oxides added to the flue gas stream, the same general trends in the recovery and distribution of ammonium ion and phosphate species at 160 and 90 °C (Tables 8 and 9) were observed as those trends observed in the absence of added reactive gases to the flue gas stream. These results indicate that gaseous ammonia and particulate phosphate species in the flue gas stream recombined into ammonium phosphate salts at 160 and 90 °C, with the extent of recombination increasing as the temperature was lowered. From the thermodynamic considerations discussed earlier, the most probable recombination product at 160 and 90 °C is monoammonium dihydrogen phosphate, $NH_4H_2PO_4$.

From the ion chromatographic analyses of the filter washes, sulfate ion and nitrate ion were found to be present at concentrations comparable to or greater than the concentrations of orthophosphate. Thus, in the presence of added oxides of sulfur and nitrogen, there appears to be a competition for the available ammonia in the gas stream during recombination reactions at 160 and 90 °C among orthophosphate, sulfate, and nitrate ions. The background level of sulfur trioxide in the gas stream was the source of the sulfate species in these experiments. The background concentration of sulfur trioxide was measured and found to average approximately 2 ppm (0.1 μmol/l, expressed for 25 °C) with an average concentration of 600 ppm sulfur dioxide in the gas stream. The concentration of nitrate ion in the gas stream, on the other hand, was expected to be on the trace level. The source of the nitrate ion is assumed to be the oxidation of ammonia by the nitrogen oxides added to the gas stream. However, as was pointed out earlier, the average input concentration of phosphate ion into the gas stream at 650 °C in these experiments was so small (0.25 μmol/l, only two-and-a-half times greater than the average sulfur trioxide background level) and the apparent wall losses were so great that there is little significance to the observed competition between the phosphate ion and the sulfate and nitrate ions for the available ammonia in the gas stream. In the presence of a large excess of phosphate ion relative to sulfate and nitrate ions, the competition might be negligible.

Reaction of Ammonia with Nitrogen Oxides. Table 8 shows that when nitrogen oxides were present in the gas stream during the injection of LPA-445, the ammonia recoveries at 160 and 90 °C were significantly less than those in the absence of added nitrogen oxides. The average recovery of ammonium ion was 34% at 160 °C with sulfur dioxide as the only reactive oxide added to the gas stream. With both sulfur dioxide and nitrogen oxides added to the gas stream, the recovery of ammonium ion averaged only 13%, less than one-half the recovery found at 160 °C with no nitrogen oxides present. This observation is consistent with the gas stream reaction of nitrogen oxides with ammonia at 650 °C observed during the investigations of ammonia and ammonium sulfate.

Phosphine Determination

No measurable concentrations of phosphine could be found in flue gas samples taken from the outlet of the electrostatic precipitator (160 °C) or the outlet of the 90 °C zone in the absence of added reactive gases or in flue gas samples from the 650 °C reaction zone during the injection of LPA-445 into flue gas containing added oxides of sulfur and nitrogen.

CONCLUSIONS

Coaltrol LPA-40

Apollo Chemical Corporation's Coaltrol LPA-40 was found to consist of an aqueous solution of ammonium sulfate. The formulation was injected into a simulated flue gas at 650 °C, and the gas stream was sampled downstream from the point of injection at flue gas temperatures of 650, 160, and 90 °C. The high injection temperature was selected because of Apollo's practice of injecting LPA-40 ahead of the economizer in a full-scale power plant.

At 650 °C, ammonium sulfate decomposed primarily into its constitutent compounds: ammonia, sulfur trioxide, and water. Upon cooling of the flue gas to 160 or 90 °C, recombination of the molecular fragments occurred. Ammonium bisulfate appeared to be the principal recombination product at 160 °C, and ammonium sulfate seemed to be predominant at 90 °C.

The implications of these results with respect to stack emissions are that some ammonia may be present in the stack emissions, and ammonium salts may also be present if these solids are not effectively removed in the electrostatic precipitator. Ammonia stack emissions appear to be less likely when the flue gas contains large concentrations of nitrogen oxides due to the apparent chemical reaction of ammonia with nitrogen oxides at high flue gas temperatures.

Coaltrol LPA-445

Coaltrol LPA-445 was found to consist of an aqueous solution of diammonium hydrogen phosphate. The formulation was injected at 650 °C, inasmuch as Apollo recommends high temperature injection to produce thermal decomposition of the ammonium phosphate.

Decomposition of diammonium hydrogen phosphate to ammonia and unidentified phosphate species appeared to occur at 650 °C. Recombination of the high temperature fragmentation products was observed at 160 to 90 °C. The most logical explanation for the mechanism of recombination was that ammonia and phosphate species recombined principally as ammonium dihydrogen phosphate (with the mole ratio of ammonium ion to phosphate ion being 1:1 rather than 2:1 as at the beginning). A considerable excess of ammonia vapor remained in the gas stream after the solid phosphate was removed by filtration.

It thus appears that some ammonia will be emitted from the stack of a power plant when LPA-445 is used for conditioning, although the amount emitted may be decreased when large concentrations of nitrogen oxides are present in the flue gas. If not removed by electrostatic precipitation, ammonium dihydrogen phosphate particles will also be emitted.

REFERENCES

1. Small, H., T. S. Stevens, and W. C. Bauman. Novel Ion Exchange Chromatographic Method Using Conductimetric Detection. Anal. Chem., 47:1801-1809, 1975.

2. Harwood, J. E., and A. L. Kühn. A Colorimetric Method for Ammonia in Natural Waters. Water Res., 4:805-811, 1970.

3. Fritz, J. S., and S. S. Yamamura. Rapid Microtitration of Sulfate. Anal. Chem., 27:1461-1464, 1955.

4. Kitson, R. E., and M. G. Mellon. Colorimetric Determination of Phosphorus as Molybdivanodophosphoric Acid. Ind. Eng. Chem., 16:379-383, 1944.

5. Kelley, K. K., C. H. Shomate, F. E. Young, B. F. Naylor, A. E. Salo, and E. H. Huffman. Thermodynamic Properties of Ammonium and Potassium Alums and Related Substances with Reference to Extraction of Alumina from Clay and Alunite. Technical Paper 688. U. S. Bureau of Mines, Washington, D. C., 1946. pp 66-69.

6. Scott, W. D., and F. C. R. Cattell. Vapor Pressure of Ammonium Sulfates. Atmos. Environ., 13:307-317, 1979.

7. Halstead, W. D. Thermal Decomposition of Ammonium Sulphate. J. Appl. Chem., 20:129-132, 1970.

8. Erdey, L., S. Gal, and G. Liptay. Thermoanalytical Properties of Analytical-Grade Reagents—Ammonium Salts. Talanta, 11:913-940, 1964.

9. Bennett, R. P., and M. J. O'Connor. Method of Conditioning Flue Gas to Electrostatic Precipitator. U. S. Patent 4 043 768, August 23, 1977. Assigned to Apollo Chemical Corporation, Whippany, New Jersey.

10. Bennett, R. P., M. J. O'Connor, A. E. Kober, and I. Kukin. Method of Conditioning Flue Gas to Electrostatic Precipitator. U. S. Patent 4 042 348, August 16, 1977. Assigned to Apollo Chemical Corporation, Whippany, New Jersey.

11. Goksøyr, H., and K. Ross. The Determination of Sulfur Trioxide in Flue Gases. J. Inst. Fuel, 35:177-179, 1962.

12. Maddalone, R. L. *Guidelines for Combustion Source Sulfuric Acid Emission Measurements*. TRW Document No. 28055-6005-RU-00. TRW Defense and Space Systems Group, Redondo Beach, California, 1977. 14 pp.

13. Recommended Method of Analysis for Nitrogen Dioxide Content of the Atmosphere (Greiss-Saltzman Reaction). In: *Methods of Air Sampling and Analysis*, M. Katz, Ed. American Public Health Association, Washington, D. C., 1977. pp 527-534.

14. Tentative Method of Analysis for Total Nitrogen Oxides as Nitrate (Phenoldisulfonic Acid Method). In: *Methods of Air Sampling and Analysis*, M. Katz, Ed. American Public Health Association, Washington, D. C., 1977. pp 534-538.

15. West, P. W., and G. C. Gaeke. Fixation of Sulfur Dioxide as Sulfitomercurate III and Subsequent Colorimetric Determination. *Anal. Chem.*, 28:1816-1818, 1956.

16. Phosphate/Stannous Chloride Method. In: *Standard Methods for the Examination of Water and Wastewater*, 14th ed., M. C. Rand, A. E. Greenberg, and M. J. Taras, Eds. American Public Health Association, Washington, D. C., 1975. pp 479-480.

17. Dechant, R., G. Sanders, and R. Graul. Determination of Phosphine in Air. *Am. Ind. Hyg. Assoc. J.*, 27:57-79, 1966.

18. Passillé, A. Dissociation of Ammonium Phosphates. *Comptes rendus*, 199: 356-358, 1934.

19. Warren, T. E. Dissociation Pressures of Ammonium Orthophosphates. *J. Am. Chem. Soc.*, 49:1904-1908, 1927.

BIOTOXICITY OF FLY ASH PARTICULATE

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Abstract

Fly ash samples were collected as part of field tests of electrostatic precipitators on boilers fired with coal of varying sulfur content, and from hopper and stack plumes. The filter samples were obtained by isokinetically sampling flue gas. Collection temperatures ranged from ambient to 350°C. A known weakly mutagenic fly ash was supplied by Battelle (Columbus).

The mutagenic potential of fifteen fly ash samples from five coal-fired power plants was evaluated. Mutagenicity was assessed utilizing the *Salmonella*/Mammalian microsome assay, employing bacterial strains TA1535, TA100, TA1537, TA1538, and TA98. Fourteen samples were negative for mutagenicity; although some of these materials exhibited varying cytotoxicity to Chinese Hamster Ovary cells as measured by a number of parameters. One previously tested fly ash (Battelle Columbus Laboratories) generated a positive mutagenic response. The effect of solvent extraction on the apparent mutagenicity of the Battelle Fly Ash was investigated. The effect of sampling temperature, extraction procedure, and particulate size on the determination of apparent mutagenicity is discussed.

BIOTOXICITY OF FLY ASH PARTICULATE

INTRODUCTION

Western nations and Japan, faced with the eventual shortage of commonly used fossil fuels, must now develop technologies to exploit more abundant less-efficient alternative fuel sources. A greater world population density resulting from increased net population growth in this century must now be considered when planning new energy programs, because of the possible attendant human health risk resulting from pollutant streams generated by new energy producing industries, and from production industries planning to utilize low-efficiency, low grade fuels.

The enormous number of xenobiotic (synthetic, non-biological) substances being presented to the environment each year has inumdated the capacity for assessing their insult to human health and to the environment. Until very recently, classical toxicological methodology was nearly completely restricted to studies with whole animals. Table 1 illustrates the large investment in time and cost required to test the toxicity of single substances using whole-animal protocols. The endpoints measured here were carcinogenicity, and general toxicity determined by acute (death-producing) protocols, and are compared to the much smaller investment required to determine the same endpoints using recently-developed *in vitro* bioassay techniques.

Toxicity from substances present in synthetic fuels production effluents and other industrial pollutants is not restricted to cancer risk; there is a possibility of organ-specific toxicity as well (lung, nervous system, liver, reproductive organs, etc.). In this respect, teratological effects and disorders of development must also be considered. Although this report will be concerned only with the mutagenic/carcinogenic and general cytotoxic potential of energy production byproducts and effluents, other attendent health risk possibilities must not be forgotten; especially in the case of the neonate or infant, where developing organ-systems are often more susceptible to the effects of environmental agents than the adult (Press, 1978)[1].

DESCRIPTION OF TEST SAMPLES AND BIOASSAY

Sampling Procedure

The fly ash samples used in this study were collected during extensive field tests of electrostatic precipitators (ESP), collecting fly ash from combustion of coal. The samples were collected at five different plants by two different EPA contractors (Southern Research Institute and Air Pollution Technology, Inc.). Brief information on the different plants is given in Table 2.

Except for plants 1 and 5, where only hopper samples were obtained, filter samples were obtained by isokinetic sampling of the flue gas. The filter was maintained at the flue gas temperature, which was essentially the same as the ESP operating temperature. At the end of the sampling period the filters were cooled and placed in sealed containers, which were shipped to EPA's Industrial Environmental Research Laboratories/ Research Triangle Park, and given to Research Triangle Institute. The samples from plants 3 and 4 were stored at EPA's Industrial Environmental Research Laboratories/Research Triangle Park for some time prior to Ames testing. The plant samples were tested shortly after they were received from the field.

Inorganic flue gas conditioning agents were used at plants 2,3, and 4 to improve the performance of the ESP's at these plants. Sulfur trioxide (SO_3), was used at plants 2 and 3 while a proprietary agent was used at plant 4. This agent is believed to be an ammonium phosphate salt. Particulate samples were obtained for these 3 plants, both with and without flue gas conditioning. In all cases, samples at the outlet or the ESP were obtained. Both inlet and outlet samples were obtained at Plant 2.

Extraction Procedure

Two extraction procedures were employed with the E.P.A. particulate fly ash samples. Samples A1001 were added directly to dimethylsulfoxide (spec. grade) and exposed to sonic disruption. A1010 through A1014 fly ash particulates were extracted using 20 ml cyclohexane-methanol (50% by volume) and sonication. The solvent extract was then evaporated to dryness under nitrogen and the solute transferred to dimethylsulfoxide.

Four solvents were employed to extract the Battelle samples: horse serum, water, cyclohexane-methanol, and methylene chloride. Horse serum was selected for its chemical and physiological similarity to lung alveolar fluid; the serum protein forms soluble complexes with some carcinogenic heavy metals (Chrisp, et al.)[2]. Water was used by Battelle. Cyclohexane-methanol, a nonpolar nonmutagenic solvent, was utilized for extraction of polar organics while methylene chloride was employed for extraction of nonpolar organics. Both horse serum and deionized water were incubated with ash for 48 hrs at 37°C prior to bioassay. The cyclohexane-methanol and methylene chloride extracts were separated from the particulate by filtration and the solute evaporated to dryness under nitrogen and suspended in dimethylsulfoxide. EPA fly ash particulates remained in suspension in vehicle, while the Battelle sample was filtered prior to bioassay.

Ames/Salmonella Mutagenesis Bioassay

The Ames/Salmonella bioassay provides a rapid, sensitive screening procedure for determining the mutagenic potential of a given chemical substance or complex mixture in a genetically well-defined system (Ames, 1979)[3]. The specific Salmonella strains employed (TA98, TA100, TA1538, TA1535, TA1537) allow determination of the class of mutagen (base substitution, frame shift etc.) being evaluated (Ames, 1979)[3]. The Salmonella strains utilized carry mutations in the histidine genes; such that the normally prototrophic bacteria now requires histidine in the growth medium due to their inability to synthesize histidine, de novo. When a substance interacts with the DNA at or very near the site of the original point mutation, the reading frame may be corrected by the second mutation, reverting the bacterium to protorophy - or enabling the bacterium to once again grow in minimal medium void of histidine supplement. This is termed a reverse mutational event. Different mutational events (base pair substitution and frameshift mutations) are detected by the bacterial strains employed: TA98, TA1538, and TA1537 detect frame-shift mutations while TA100 and TA1535 are utilized to detect base-pair substitutions (non-sense, or mis-sense mutations).

As many as 10^6-10^7 bacteria can be plated on a 100 mm diameter culture dish in minimal medium. The fraction of revertant bacteria which have acquired mutations in the histidine gene can be scored by couting the number of colonies (arising from individual revertants) growing on minimal medium void of histidine.

Many substances are metabolically transformed in mammalian tissue to mutagenic/carcinogenic intermediates; these substances would exhibit no mutagenicity in the Ames assay without prior metabolic activation. Therefore, microsomal preparations (with increased enzyme activity) from Aroclor-induced rat livers, which metabolize procarcinogens to their proximate carcinogens, are incorporated into the bioassay (Ames, et.al., 1975)[4]. Thus, the resultant assay can detect different classes of mutagens/carcinogens (requiring, or not requiring metabolic activation), as well as different mutational events (frame-shift, substitutions, etc).

Mammalian Cell Cytotoxicy Assays

Mammalian cells grown in tissue culture might serve as a substitute for the whole animal as a screening tool for assessing the cellular toxicity of xenobiotics to mammals. In this assay, a stable tissue-culture cell line with well known growth characteristics and biochemistry would serve as the test system. The putative toxins would challenge the cells by addition to the growth medium when the cells are growing as a monolayer, attached to a plastic substrate (plastic culture dish). The cell type chosen for this study is the Chinese Hamster Ovary (CHO) cell line introduced in 1967 as a parent diploid cell for the production of mutant cells (Kao and Puck, 1967)[5]. The cell line is available from the American Type Culture Association, and although no longer diploid, posesses a constant chromosome number (ploidy), is fairly resistant to infections, is relatively easy to maintain in culture on defined medium, and divides rather rapidly (12-14 hr doubling-time) for a mammalian cell. The CHO cells grow in a uniform population and the levels of various key metabolites involved in their metabolism can readily be measured. The CHO cell exhibits consistent growth kinetics when cultured under standard conditions of pCO_2 and pO_2, temperature and humidity, and when provided with a standard nutrient culture medium containing serum, salts and essential amino acids. When exposed to a known cytotoxin (we have chosen Cadmium; Ozawa, et al., 1976)[6] the growth and metabolism of the CHO cell is affected (Winiger et al., 1978)[7].

Inhibition of cell growth is determined in this study by two assay methods. In the first, cells are explanted onto a growth substrate by seeding 10^5 cells into a 35 mm diameter plastic culture dish, allowing 24 hrs. for cell attachment, and incubating with the compound to be studied for 24 hrs. The medium is then replaced with fresh medium, and the dishes incubated for about one week, with cell counts of control and treated cultures performed at 24 hr. intervals. A control growth curve, exhibiting the lag, logarithmic, and stationary phases of growth is depicted in Figure 1. The effect of Cadmium is also shown.

The second method quantitates the ability of a single CHO cell to give rise to a viable colony (or clone) of cells. This cloning efficiency assay is performed by seeding a small number of cells (200-1000) in a 60 mm culture dish, allowing 24 hrs. for attachment, adding test substance, incubating for 24 hrs., replacing medium, and incubating about 10 days, or until colonies of cells grow large enough to count. These two cell-growth studies provide an overall screening assay to quantitate general cytotoxicity, where the parameters measured are the ability of cells to grow and divide as members of a large population, and the ability of a single cell to survive the toxic insult, and give rise to progeny.

MATERIALS AND METHODS

Ames Mutagenesis Bioassay

Chemicals. NADPH (tetrasodium salt, Type 1) and known positive mutagens (highest purity available) were obtained from Sigma Chemical Company. Dimethylsulfoxide (spectrophotometric grade) and sucrose were obtained from the Fisher Chemical Company. Agar (Difco Bacto-Agar®) was obtained from Difco Laboratories.

Bacterial Strains. Tests were conducted with *Salmonella typhimurium* strains TA100, TA1535, (utilized to detect base-pair substitution mutagens), and strains TA1537, TA1538 and TA98 (employed for detection of frameshift mutagens). All histidine auxotrophic strains were obtained directly from Bruce Ames (Biochemistry Department, University of California, Berkeley).

CHO Cytotoxicity

Tissue culture medium was obtained from KC Biologicals (Lanexa, Kansas) and from Grand Island Biologicals (N.Y.). Cells were obtained from the American Type Culture Association. Disposable tissue culture dishes, flasks and pipettes were obtained from Corning Corp. All water used in preparing medium was triple distilled after passing through ion-exchange resins.

Standard Protocols

Ames Mutagenesis Assay. The procedures for handling the strains and preparing media components were those of Ames *et al*., 1975)[4], with the following exceptions: (a) Craig-Dawley male rat livers were used as the source for metabolic activation (S-9) [activation potentials were very similar to Sprague-Dawley male rats (data not shown)], (b) NADPH was added directly to the plate (per plate, 0.10 ml containing 0.32 mg NADPH), (c) use of a 2.5 ml agar overlay rather than a 2.0 ml overlay; (d) S-9 microsomal preparation was diluted in 0.25 M sucrose at a concentration of 30 mg protein/ml and added at protein concentrations of 3.0mg/ plate for initial testing; (e) bacterial strains are centrifuged and concentrated in normal saline at 10^{10} cell/ml. The S-9 microsomal preparation was obtained from rats injected with Aroclor 1254. Protein was measured by the method of Lowry *et al*., (1951)[8].

All test components were added at 100 µl per plate. All dose levels were performed in triplicate and duplicate experiments were performed on separate days if sample was available.

For quality assurance, the test is divided into five parts:

Toxicity Testing, Plate Incorporation Method. 200-300 cells per petri dish are plated on histidine containing medium (histidine positive). Toxicity tests were done with and without induced S-9. Test compound was added at 0.1 ml/plate in all tests. The viability ratio was calculated as the ratio of surviving colonies with sample to colonies without sample. The schematic of the test procedure is illustrated in Figure 2.

Mutagenesis Testing, Plate Incorporation Method. *With S-9*--To a tube containing 2.5 ml of agar void of histiding (histidine negative) was added 0.1 ml of S-9 microsomal preparation, 0.1 ml of NADPH, 0.1 ml of a solution of test material or positive control compound in dimethylsulfoxide, and 0.1 ml of bacterial suspension. *Without S-9*--Prepared as above, 0.1 ml of test material or positive control, 0.1 ml of bacterial suspension and 0.1 ml of sucrose and deionized water.

Sterility Testing, Plate Incorporation Method. Sterility tests are conducted with histidine-positive overlay plates, using the amounts of components employed in the tests. Components tested were: sample, positive controls, solvent, water, 0.25M sucrose solution, saline, microsomal preparation (S-9), and NADPH solution.

Negative Control, Plate Incorporation Method. Solvent control was taken through the bioassay, and tested for toxicity, mutagenicity and effect on the metabolic activation S-9 microsome system.

Positive Mutagen Control Testing, Plate Incorporation Method. Using histidine-negative overlay, 10^7 cells were plated in each dish. Known mutagens were tested to assure that the strains were active and the microsomal preparation was activating promutagens [illegible] the desired levels. If known positive controls do not show proper mutagenic activity, the test components (cultures and/or microsomes) are rejected. Control compounds currently in use are:

Strain	Without S-9	With S-9
TA 1535	Sodium azide 200, 20, 2 μg/plate	2-Anthramine 100, 10, 1 μg/plate
TA 1537	Quinacrine HCl 250, 25, 2.5 μg/plate	2-Anthramine 100, 10, 1 μg/plate
TA 1538 TA 98	2-Nitrofluorene 100, 10, 1 μg/plate	2-Anthramine 100, 10, 1 μg/plate
TA 100	Sodium azide 200, 20, 2 μg/plate	2-Anthramine 100, 10, 1 μg/plate

Mutagenesis Data. No test is considered positive unless all four sections of the assay are performed, and the spontaneous reversion rate determined. The experiment is discarded if the spontaneous background exceeds normally observed values, if positive controls are not acceptable, or if the sterility test indicates contamination. Mutagenic ratios of 3 or greater, determined on the linear portion of the dose-response curve are considered positive.

Cytotoxicity Testing: Growth Kinetics

Chinese Hamster Ovary cells were obtained from the American Type Culture Association, explanted in Ham's F12 tissue culture medium supplemented with 10% fetal calf serum. The cells are explanted and grown to confluence, the monolayer dispersed, cells diluted with medium containing 10% DMSO and frozen at -80°C in 1 ml aliquots for storage, and are subsequently thawed and cultured for experiments. No antibiotics were used in the following experimental protocol. Cells were seeded at 10^5 cells/35 mm culture dish in 2 ml medium, and incubated at 37°C in a 5% CO_2 atmosphere. Three dishes were used for each time point of 6 points measured (24 hours apart) after 24 hours incubation with a sample added in not more than 25 μl DMSO vehicle. After incubation with sample, the medium is discarded and replaced with 2 μl fresh medium. The cell monolayer is dispersed with 0.05% trypsin and the cells counted using a Fisher automated cell counter.

Cloning efficiency. Chinese Hamster Ovary cells, obtained from the source described above, and cultured as described above, are explanted in 60 mm dishes at 200 and 1,000 cells per dish in 5 ml F12 medium with 10% calf serum and no antibiotics. The cells are incubated for 24 hours to attach, the test substance added in 10 and 25 μl DMSO, incubated 24 hours, the medium replaced with fresh medium, and the cells incubated until visible colonies arise (about 6-10 days). At this time, the medium was removed, the colonies washed with methanol, stained with methylene blue, and counted with an automatic colony counter. Control colony formation was done with 25 μl DMSO added to the medium.

Quality Control and Assurance Procedures: Ames Mutagenesis Bioassay

Sample Receipt and Dilution Procedures. Extracted samples are immediately stored at 4°C. Dilution with spectral grade DMSO (N_2 bubbled) is done under an operating fume hood (yellow lights are used to avoid photodeactivation).

Salmonella Strain and S-9 Activation Validations. Quality control and assurance procedures were undertaken to insure proper functioning of bacterial strains and microsomal preparations. In general, our quality assurance and control requirements are in agreement with those suggested by DeSerres and Shelby (1979)[9].

RESULTS

Ames Mutagenesis Bioassay Results

Table 2 illustrates the fly ash particulate results from the Ames/ Salmonella assay. Results were negative for mutagenicity under all conditions tested. Toxicity to the bacterial strains was apparent for several samples, as shown in Table 2.

The Battelle Laboratory fly ash data is given in Table 3. Battelle Laboratories found a water-extract of this sample to be weakly mutagenic for TA98; a mutagenic ratio of 3.5 was obtained. This response required S-9 activation. We determined a mutagenic ratio of 3.4 for TA98 requiring S-9 activation, but only the methylene chloride extract was active.

Toxicity determinations are as follows: Both the cyclohexane/methanol and methylene chloride extracts were toxic for bacterial strains TA98 and TA100 (without S-9 addition). Water and dialized horse serum extracts were nontoxic to both strains with and without S-9 addition. Table 3 illustrates that while toxicity decreased with metabolic activation, mutagenic activity increased.

Chinese Hamster Ovary Cell Cytotoxicity Results

Fourteen fly ash samples were tested for toxicity by the growth inhibition and clonal toxicity methods using 50 and 125 μg samples. The method was validated using $CdCl_2$ at various concentrations from 10^8 M. The validation results are shown in Figure 1. At concentrations as low as 10^{-7}M, CdCl inhibits growth of CHO cells, and as the Cd concentration is increased, the effect becomes more pronounced. Figure 3 illustrates the effect of 50 and 125 μg of fly ash particulate added to the cells in 10 and 25 μL DMSO as described above. A marginal affect was noted. Sample A1008, a hopper sample from a high sulfur Eastern coal-fired power plant, exhibited medium toxicity measured by the growth kinetic method. This sample was also toxic to the Salmonella (Table 2). None of the remaining 13 samples exhibited really significant toxicity at the concentrations tested, agreeing with the mutagenicity findings.

DISCUSSION

Several investigations of the mutagenicity of fly ash have been reported. Natush and Tomkins (1978)[10] predicted that temperatures near 100° are critical for adsorption of polynuclear aromatics onto fly ash particulate. Fisher et al., (1979)[11] have shown that heating coal fly ash to 350°C, eliminates mutagenicity, consistent with the hypothesis that the bulk of the mutagenicity originates from organic constitutents which volatilize at 350°C. Natusch et al., (1979)[12] and Fisher et al., (1979)[11] have reported the mutagenicity of fly ash to be greatest in the finest (submicron sized) particles, which have the greatest surface area per unit mass. These submicron particles have the longest atmospheric residence time, are the most efficiently deposited in the lung, and are the least efficiently removed. Chrisp et al., (1978)[2] Fisher et al., (1979)[11] also reported the E.S.P. collected particulates (whether size classified or not) were not mutagenic, while stack-collected respirable particulates were mutagenic. It was presumed by these authors that failure to control mutagens was due to E.S.P. collection temperatures in excess of 100°, resulting in volatilization of organic mutagens which were thus not collected by the E.S.P.

Failure to detect mutagenicity in the 14 fly ash samples tested in this study may have been due to inefficient extraction procedures. Weak mutagenicity detected for the Battelle sample may be a result of the very low organic content (<0.1%) of most fly ash samples. Failure to remove the inorganic matrix permits readsorption of organics onto the particulate during solvent evaporation, inhibiting mutagenic potential. Concerning possible control technology, it is suggested that volatilized mutagenic organics may condense onto cooled inorganic particulate downwind of a stack where ambient temperatures are realized.

References

1. Press, M.F., Lead Encephalopathy in Neonate Long Evans Rat: Morphologic Studies. J. Neuropath. Exp. Neurol. 36: 169-193, 1977.
2. Crisp, C.E., G.L. Fisher, J.E. Lammert. Mutagenicity of Filtrates from Respirable Coal Fly Ash. Science Vol. 199 January 6, 1978 pp 73-75.
3. Ames, B. N., Identifying Environmental Chemicals Causing Mutations and Cancer. Science, 204: 587-593, 1979.
4. Ames, B.N., J. McCann, and E. Yamasaki. Methods for Detecting Carcinogens and Mutagens with the Salmonella Mammalian Microsome Mutagenicity Test. Mutat. Res., 31: 347-364, 1975.
5. Kao, F. and T. Puck. Genetics of Somatic Mannalian Cells. IX. Properties of Chinese Hamster Cell Mutants with Respect to the Requirements for Proline. Genetics, 55: 513-524, 1967.
6. Ozawa, K., A. Sato, and H. Okada, Differential Susceptibility of L Cells in the Experimental and Stationary Phases to Cadmium Chloride. Japan J. Pharmacol. 26: 347-351, 1976.
7. Winiger, H., F. Kukik, and W. Rois, In Vitro Clonal Cylotoxicity Assay Using Chinese Hamster Ovary Cells (CHO-K1) for Testing Environmental Chemicals. In Vitro 14: Abstract no. 193, 1978.
8. Lowry, O.H., N.J. Rosebrough, A.L. Farr, and R.J. Randall, Protein Measurement with the Folin Phenal Reagent. L. Biol. Chem. 193: 265-275 (1951).
9. DeSerres, F., and M. Shelby. The Salmonella Mutagenicity Assay: Recommendations. Science, 203: 563-565, 1979.
10. Natusch, D.F.S., and B.A. Tomkins, Polynuclear Aromatic Hydrocarbons, Carcinogenesis 3, P.W. Jones and A.I. Freudenthal, eds., Raven Press, pp 145-153 (1978).
11. Fisher, G.L., C.E. Crisp, O.G. Raabe. Physical Factors Effecting the Mutagenicity of Fly Ash from a Coal-Fired Power Plant. Science, Vol. 204, May 25, 1979, pp 879-881.
12. Natusch, D.F.S., J.R. Wallace, C.A. Evans, Jr., Science 183, 202 (1974).

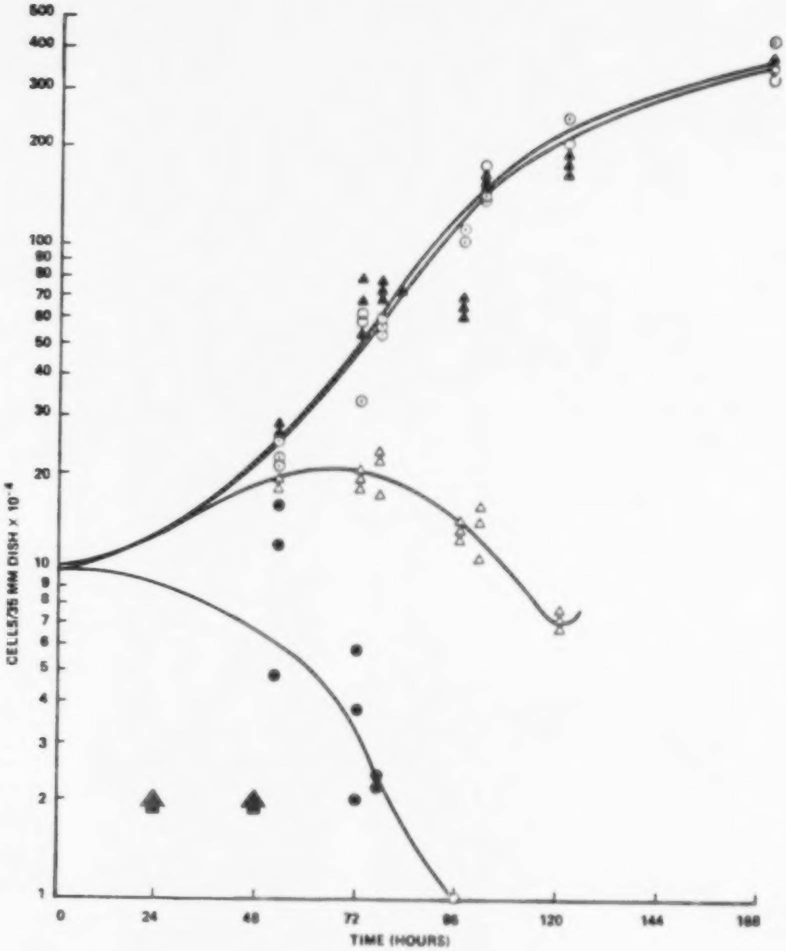

Figure 1. The Effect of Cadmium on the Growth of Chinese Hamster Ovary Cells.

BHK1 Chinese Hamster Ovary cells (10^5 cells/plate) were explanted in 35 mm diameter dishes in 2 ml F12 (Harris) culture medium, incubated 24 hr at 37°C with 5% CO_2. Cadmium was added in 25 µl DMSO at a final concentration of 10^{-8} M (▲), 10^{-7} M (△), 10^{-6} M (●). Control cells were grown in the presence of 25 µl DMSO (⊙, ○). After 24 hrs., the medium was discarded, replaced with 2 ml fresh medium, and the cells of 3 plates counted at 24 hour intervals, as described in the text.

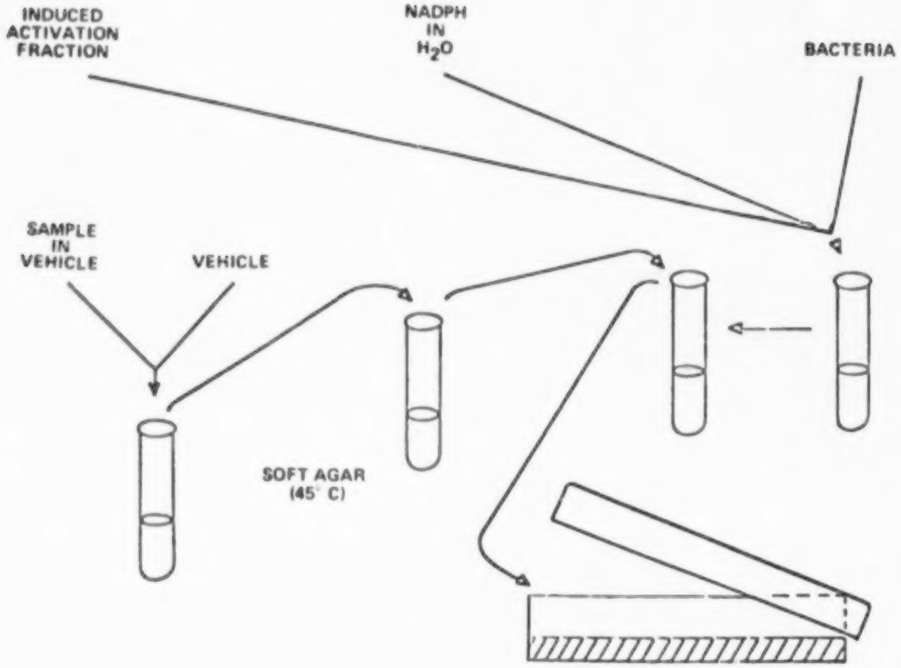

Figure 2. Scheme of Ames/Salmonella Test Procedure.

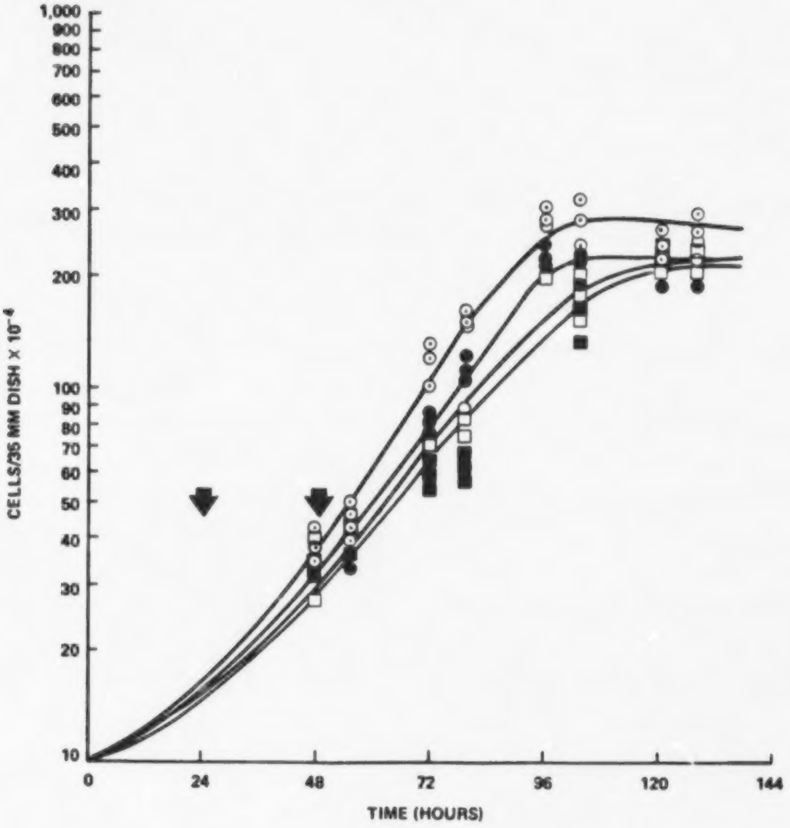

Figure 3. The Effect of Selected Fly Ash Particulate Samples on the Growth of Chinese Hamster Ovary Cells.

Fly ash particulate in 25 µl DMSO (from Plant 4,A1008; 300 µg □ ; 150 µg ■) was biotested as described in the text and in the legend to Figure 1. Control cells were grown in 30 µl DMSO (●), and with no added DMSO (⊙).

Table 1. RELATIVE EFFICIENCY OF IN VIVO AND IN VITRO BIOTESTING FOR ENVIRONMENTAL BIOTOXICITY

	Per Substance	
	Time Required (Yrs.)	Cost (Dollars)
NCI Whole Animal Carcinogenesis	3.5	2.5×10^5
NCTR Whole Animal Toxicity	1.2	1.5×10^5
Level 1 Biotest (In Vitro Biotesting)	0.01 - 0.2	6×10^3

Table 2. SUMMARY OF BIOTESTING RESULTS OF FLY ASH SAMPLES FROM COAL-FIRED POWER PLANTS

LABORATORY CODE NUMBER	EXTRACTION PROCEDURE	PLANT NUMBER	COLLECTION TEMPERATURE	TYPE OF COAL UTILIZED IN COMBUSTION	REMARKS	AMES/SALMONELLA MUTAGENICITY	(Strain) TOXICITY	CHINESE HAMSTER KINETICS	OVARY CELLS CLONAL EFF.
A001	A	3	115°C	low sulfur western coal	SO_3 conditioning	NONMUTAGENIC	NONTOXIC	NONTOXIC	NONTOXIC
A1002	A	3	115°C	↓	STACK SAMPLE	NONMUTAGENIC	TOXIC (37,98)	NONTOXIC	NONTOXIC
A1003	A	3	115°C	↓	↓	NONMUTAGENIC	TOXIC (37,98)	NONTOXIC	TOXIC (M)
A1004	A	3	115°C	↓	↓	NONMUTAGENIC	NONTOXIC	NONTOXIC	TOXIC (M)
A1005	A	3	115°C	↓	↓	NONMUTAGENIC	NONTOXIC	NONTOXIC	TOXIC (M)
A1006	A	3	115°C	↓	↓	NONMUTAGENIC	NONTOXIC	TOXIC (L)	TOXIC (L)
A1007	A	3	150°C	↓	Hopper Sample	NONMUTAGENIC	TOXIC (37,98)	NONTOXIC	NONTOXIC
A1009	A	3	150°C	↓	Hopper Sample	NONMUTAGENIC	TOXIC ALL STRAINS	NONTOXIC	NONTOXIC
A1008	A	4	150°C	high sulfur Eastern coal	proprietary conditioning hopper sample	NONMUTAGENIC	TOXIC (37)	TOXIC (M)	-
A1010	B	5	350°C	low sulfur Western coal	no conditioning hot side E.S.P.	NONMUTAGENIC	TOXIC (98)	NONTOXIC	NONTOXIC
A1011	B	2	176°C	low sulfur Western coal high unburned carbon	SO_3 injection hopper sample	NONMUTAGENIC	TOXIC (98)	NONTOXIC	-
A1013	B	2	176°C	↓		NONMUTAGENIC	NONTOXIC	NONTOXIC	-
A1012	B	1	176°C	↓	No conditioning hopper sample	NONMUTAGENIC	NONTOXIC	NONTOXIC	-
A1014	B	1	176°C	↓	↓	NONMUTAGENIC	NONTOXIC	NONTOXIC	-

[*] Extraction Procedure

A: Addition of Dimethylsulfoxide to particulate with subsequent sonic disruption for 2 minutes.

B: The particulate materials are extracted from filters using cyclohexane methanol (50% by volume) and sonic disruption. The solvent extract is evaporated to dryness and the solute exchanged into dimethylsulfoxide.

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Table 3. MUTAGENICITY OF FLY ASH FROM BATTELLE LABORATORY

			Mutagenic Ratio				Viability Ratio			
			TA 100		TA 98		TA 100		TA 98	
Solvent	Vehicle	Dose	-MA	+MA	-MA	+MA	-MA	+MA	-MA	+MA
Cyclohexane Methanol 50% by volume	DMSO	5000	.65	1.09	1.17	1.70	.16	1.15	.54	1.20
		1000	.79	1.01	1.45	1.08	.66	1.17	.69	1.12
		600	.93	1.01	.78	.90	.88	1.08	.78	1.09
		250	.96	.95	.88	1.34	.91	1.09	.67	1.16
		100	.99	.90	.97	.94	1.22	.99	.96	.97
Methylene Chloride	DMSO	5000	.68	1.06	.71	3.41 ←	.22	1.15	.06	1.21
		1000	.85	1.12	1.06	1.22	.75	.92	.13	1.29
		500	.95	1.01	.89	1.09	.73	1.01	.52	1.35
		250	.88	1.05	.82	.95	.90	1.00	.58	1.30
		100	.96	.87	1.10	1.39	1.02	.90	.86	1.14
Deionized H_2O 37°, 48 hrs.	H_2O	5000	1.03	1.17	1.35	1.83	.95	1.11	1.12	1.15
		1000	1.13	1.19	1.68	1.59	.89	1.13	1.30	1.14
		500	1.02	1.07	1.60	1.63	.84	.93	1.29	1.14
		250	1.01	.98	1.27	1.07	.99	.96	1.10	1.04
		100	1.00	.98	1.19	1.60	.76	1.04	.89	1.06
Horse Serum dialized 37°, 48 hrs.	Horse Serum	5000	.88	.90	.86	1.38	.94	.99	.95	.99
		1000	.95	.98	.88	1.00	.95	1.08	1.02	1.01
		500	.97	.93	.67	1.27	.86	1.08	.98	1.05
		250	1.08	1.02	.83	1.19	.86	1.10	1.07	1.10
		100	1.03	.98	.84	1.28	.77	.90	.86	1.00
Positive Control	DMSO		11.98	17.05	59.19	53.25				
Solvent Control			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

FABRIC FILTERS VERSUS ELECTROSTATIC PRECIPITATORS

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Presented at the Second Symposium on the Transfer and Utilization of Particulate Control Technology. Sponsored by the U. S. Environmental Protection Agency and the Denver Research Institute. July 23-27, 1979; Denver, Colorado.

ABSTRACT

Control of particulate emissions from pulverized coal fired steam generators is becoming a significant factor in the siting and public acceptability of large coal burning power plants. The particulate emission limit established by the EPA for new coal fired boilers is 0.03 lb/10^6 Btu (13 ng/J). Possibly more restrictive than this is the State of New Mexico's particulate regulation which calls for no more than 0.05 lb/10^6 Btu (22 ng/J) total, and no more than 0.02 lb/10^6 Btu (9 ng/J) less than 2 microns in diameter. This paper will evaluate the effect of these stringent limitations on the technical feasibility and economics of dry particulate removal. Electrostatic precipitators have been the dominant particulate collection device in the electric utility industry for many years because of their low capital and operating cost. However, increasingly stringent emission standards have led to substantially higher costs for precipitators. These costs have increased sufficiently for fabric filtration to become a competitive alternative in achieving cost effective control. This paper will compare the economics and performance of fabric filtration with respect to conventional electrostatic precipitators. The paper will also address the preliminary evaluation procedures that should be followed in order to select the appropriate device for new or existing coal-fired boilers.

FABRIC FILTERS VERSUS ELECTROSTATIC PRECIPITATORS

INTRODUCTION

The particulate emission limit initially set by the EPA under provisions of the Clean Air Act of 1970 for large, new coal fired boilers was 0.1 lb/10^6 Btu (43 ng/J). Under the Clean Air Act of 1977, EPA promulgated on June 11, 1979, (Federal Register, Vol. 44, Page 33581) a New Source Performance Standard for particulates of 0.03 lb/10^6 Btu (13 ng/J). Possibly more restrictive (because of the limit on fine particulate) than this are the State of New Mexico's limits for new plants of 0.05 lb/10^6 Btu (22 ng/J) for total particulates and 0.02 lb/10^6 Btu (9 ng/J for particulates less than 2 microns in diameter. These more stringent particulate emission limitations will have a definite impact on the economics of power production for new coal fired boilers.

Electrostatic precipitators have been the dominate particulate collection device in the electric utility industry for many years, because of their relatively low capital and operating costs. However, increasingly stringent emission standards have led to substantially higher costs for precipitators. These costs have increased sufficiently for fabric filters to become a competitive alternative in achieving cost effective control. This paper presents comparative data on the economics and performance of fabric filters and conventional electrostatic precipitators. The data presented are based on investigations sponsored by the Electric Power Research Institute.[1]

SUMMARY OF EPRI STUDY

The economic findings from the EPRI study are presented in Figure 1. These are 1978 levelized costs of all capital and operating expenses evaluated for the plant's 35-year life. For particulate collection at the 0.03 lb/10^6 Btu emission limit, these costs may represent 3 to 5 percent of the total cost of power production.

The levelized costs are made up of capital investment costs and operating and maintenance costs, combined by application of appropriate economic factors (plant life, finance charges, etc.) to establish present worth and equivalent revenue requirements. The levelized costs (or revenue requirements) allow the direct comparison of the various cases as shown in Figure 1. The significant components of levelized cost are shown graphically in Figure 2 and tabulated below in Table 1.

"Capital Charges" are based on a fixed charge rate of 16% per year applied to the capital investment. This category includes depreciation, minimum acceptable return on investment, income tax on return, property taxes and insurance. It is the most significant of the factors considered, averaging about 60% to 80% of the total cost. The fixed charge rate varies considerably with the tax situation of the utility, the basic cost of money and the life of the facility. A municipal or REA utility may use figures as low as 11 or 12% per year, whereas a private utility may use 18% per year or more. A lower fixed charge rate narrows the cost difference between the precipitators and the fabric filter, but not sufficiently to change the general conclusions.

"T-R Power" refers to the power consumed by the transformer-rectifier sets of the electrostatic precipitator (ESP). The amount includes both energy and demand charges. Power consumption for T-R Sets averages about 10% of the levelized cost. The "Bags" catagory covers maintenance material, labor, overhead and bag replacements both scheduled and unscheduled. For a 2 year replacement schedule, the "Bags" category represents about 17% of the total cost.

The "Fan Power" category represents cost for incremental induced draft fan power associated with the collector and associated ductwork. The reverse air fans are also included in the category for the fabric filter. For ESP's a total pressure drop of 3 inches W.C. represented about 4% of total cost. For fabric filters a 7 inch W.C. drop represented about 15% of the total cost.

Finally, the "Miscelleneous" category contains all other operating and maintenance costs plus power for the hopper heater, purge air blowers, ash system blowers and other necessary equipment.

TABLE 1
COMPONENTS OF COLLECTOR COST*

		Levelized Cost, mills/kwh				
Coal Source	Collector Type**	Capital Charges	TR Power or Bag Repl	Fan Power	Misc	TOTAL
Wyoming	HS-ESP	1.52	0.23	0.08	0.26	2.09
	ECS-ESP	1.43	0.18	0.05	0.25	1.91
	FF-20/2	0.75	0.23	0.16	0.12	1.26
	FF-20/4	0.75	0.12	0.16	0.12	1.15
	FF-40/2	0.88	0.24	0.15	0.13	1.40
N. Dakota Lignite	ACS-ESP	1.12	0.26	0.09	0.23	1.70
	FF-20/2	0.90	0.29	0.23	0.15	1.57
Alabama	HS-ESP	1.15	0.18	0.08	0.20	1.61
	ACS-ESP	1.13	0.16	0.07	0.28	1.64
	ECS-ESP	1.27	0.17	0.07	0.23	1.74
	FF-20/2	0.78	0.24	0.18	0.13	1.33
Eastern High Sulfur	ACS-ESP	1.10	0.35	0.10	0.32	1.87
	FF-20/2	0.82	0.36	0.25	0.16	1.49

* At NSPS emission level of 0.03 lb/10^6 Btu.

** See Figure 2 for explanation of collector type designation.

As shown in Figure 1 the cost of particulate collection by electrostatic precipitation increases significantly as emission limits become more restrictive. For example, decreasing the outlet particulate emission from 0.1 lb/10^6 Btu to 0.03 lb/10^6 Btu, increases the cost to own and operate a precipitator by about 30%. This percentage varies somewhat depending on the type of coal and properties of the fly ash. Costs for the fabric filter do not change over the range of emission limitations considered, since the high efficiency of a fabric filter would enable compliance with limitations from 0.01 to 0.1 lb/10^6 Btu. For the new federal limit of 0.03 lb/10^6 Btu, the economics favors the fabric filter over the precipitator for all of the coals investigated. In general, it was found that the economic comparison of precipitators and fabric filters was dependent on the particulate emission limitation, the ash content and heating value of the coal, the electrical properties of the fly ash, the bag replacement schedule of the fabric filter, and site specific aspects.

Each collector's ability to collect fine particulate matter was also studied. For the four coals considered, it was predicted that if the New Mexico limit on total emissions of 0.05 lb/10^6 Btu were met, then the limit on emissions of particles less than two microns in size also would be met. For equal outlet loadings, the fabric filter collects submicron particulate more effectively than the precipitator, and so produces correspondingly lower opacities than the precipitator. Opacity is of more concern for precipitators whereas a fabric filter normally will produce a clear plume. Computer models indicate that an opacity of 5 percent (essentially a clear stack) can be obtained with a design limit of 0.014 lb/10^6 Btu. Based on the limited experience to date, fabric filters will have a significant economic advantage in almost all cases if the design is based on obtaining a clear plume.

It should be noted that, although fabric filters have some clear advantages over precipitators, experience with these devices on large coal fired power plants and with high sulfur coal is minimal. The largest fabric filter installation to date is at the Monticello Station of Texas Utilities (equivalent to 500 MW unit). As further experience is gained with fabric filters, valuable information on reliability and cost will allow more accurate comparisons of the two particulate collectors.

CASE STUDIES

Four coals were selected for a hypothetical 500 Megawatt (MW) pulverized coal fired boiler as shown in Table 2. The collectors considered appropriate for each of these coals are also shown in Table 2. The estimated collection areas required to produce various emission levels are shown in Figure 3.

TABLE 2
SUITABILITY OF COLLECTOR SYSTEMS

Type of Coal	Suitable Collectors
Wyoming Sub-bituminous, Hanna, Wyo. Region (0.56%S)	Hot Side Precipitator European Cold Side Precipitator Fabric Filter
North Dakota Lignite High Sodium Ash (0.68%S)	American Cold Side Precipitator Fabric Filter
Alabama Bituminous Warrior River Area of Alabama (1.9%S)	Hot Side Precipitator American Cold Side Precipitator European Cold Side Precipitator Fabric Filter
Eastern Bituminous Ohio Region (4.3%S)	American Cold Side Precipitator Fabric Filter

Selection of the specific collection area (usually referred to as SCA, expressed in terms of square feet of collecting plate area per 1,000 actual cubic feet of gas per minute) is probably the most difficult and controversial procedure. The method used in the EPRI study for establishing the SCA was based on a modified form of the Deutsch Equation:

$$n = 1 - \exp\left[-\left(w \times \frac{SCA}{1,000}\right)^k\right]$$

or

$$SCA = \frac{1000}{w}\left[\ln\left(\frac{1}{1-n}\right)\right]^{1/k}$$

where n = particulate removal efficiency
w = precipitation rate, fpm
k = dimensionless parameter, used to modify the original Deutsch equation.

The value for k can vary from 0.4 to 0.6. The EPRI study used a value of 0.5. The value for w depends on the characteristics of the fly ash, primarily resistivity and mineral composition. Empirical data from existing installations were used in assigning the appropriate values in each case. The collecting plate areas shown in Figure 3 for precipitators are for specific coals from the geographical regions and can vary considerably with small changes in coal analysis. The curves shown in Figure 3 should not be construed to apply to all coals in general. Cloth area for the fabric filter changes only with gas volume to be filtered. The gross air to cloth ratio was selected at 1.81 acfm/ft^2 (1.93 net) for all cases over the range of emission limits considered.

CAPITAL COSTS

Installed costs, presented in Figure 4 for the range of outlet emission levels, are based on 20 different designs and estimates prepared for the study. Included in the estimates are materials and labor for installation of the collectors, hoppers, support steel, ducts, nozzles, dampers, fans, expansion joints, ash-handling equipment, insulation, and other miscellaneous items. Added to these are differential and indirect field costs, engineering and fee at 3 percent, and contingency and miscellaneous costs at 10 percent.[1]

Note that the capital investment for precipitators increases as the outlet emission is reduced. Since fabric filters operate at high particulate removal efficiencies with relatively constant outlet loading, the capital cost is essentially constant for the range of emission limits. The fabric filter capital cost is different for each of the four coals, since the cloth area depends on the gas volume. Options such as air-heater temperature control and preheat, for controlling the inlet flue gas temperature were not included. Some plants such as peaking or cycling units, incorporate these elements to minimize excursions through the acid dew point and to prevent corrosion to metal components or damage to the filter bags.

Detailed estimates were made for three plant sizes (or gas flow rates) and for three different precipitator collection areas. For example, the hot side precipitator was evaluated for 250, 500, and 1000 MW at SCA's 200, 400, and 800 $ft^2/10^3$ acfm. The fabric filter was estimated for these plant sizes at air-to-cloth ratios of 1.6, 2.0, and 3.0 acfm/ft^2.

Graphical representations of how capital costs were found to vary with plant size, collection area, and number of compartments (for fabric filters) are shown in Figures 5, 6, and 7. The discontinuity in cost versus gas flow for precipitators is due to layout considerations. For smaller boilers space for the precipitator is not a problem. For the larger boilers, longer (deeper) precipitators must be turned sideways (parallel or chevron arrangement) to fit in the 300 feet space allowed between the boiler house and the chimney. Thus, ducting is more extensive. Generalized relations were developed for expressing the costs as functions of design parameters, such as collection area and gas flow rate. The relations listed below allow the extrapolation of costs for collector systems of different plant size and gas flow rates.

For electrostatic precipitators (ESP):

$$CI_{ESP} = CI'_{ESP} \times \left(\frac{F}{F'} \right)^{f} \times \left(\frac{SCA}{SCA'} \right)^{s}$$

For fabric filters (FF):

$$CI_{FF} = CI'_{FF} \times \left(\frac{F}{F'}\right)^{f} \times \left(\frac{A/C}{A/C'}\right)^{a} \times \left(\frac{M}{M'}\right)^{m}$$

Where CI = capital investment; F = inlet gas flow, acfm; SCA = ESP specific collecting area, ft^2/ 1000 acfm; A/C = gross air-to-cloth ratio of the fabric filter, acfm/ft^2; M = number of compartments; f = flow exponent; s = SCA exponent; a = air-to-cloth exponent; m = module exponent; and primed variables are those of the base case. Cost-scale exponents for the four types of collectors for the base case conditions were determined from the various estimates. These are given in Table 3.

TABLE 3
EXPONENTS FOR ESTIMATING
CAPITAL COST

Collector	f	s	a	m
Hot-Side ESP	0.97	0.58	N.A.	N.A.
Cold-Side ESP (Am.)	0.93	0.60	N.A.	N.A.
Cold-Side ESP (Eur.)	0.89	0.74	N.A.	N.A.
Fabric Filter	0.72	N.A.	-0.52	0.24

The base costs and design parameters are listed below in Table 4.

TABLE 4
BASE CASE PARAMETERS AND COST

Collector System	A/C or SCA	Gas Flow (10^6 acfm)	No. of Modules	Capital Investment ($\$10^6$, 1977)
Hot-Side ESP	400	2.64	N.A.	23.9
Cold-Side ESP (Am.)	350	1.97	N.A.	14.8
Cold-Side ESP (Eur.)	550	1.97	N.A.	20.7
Fabric Filter	1.81	1.97	16	14.6

OPERATION AND MAINTENANCE COSTS

Operation and maintenance costs were estimated for collectors and ash-removal systems based on information obtained from existing installations. As shown in Table 5, operation of the collector was assumed to be constant at $20,000 per year for all collectors and $60,000 per year for ash handling.

TABLE 5

COST AND UNIT FACTORS FOR
OPERATION AND MAINTENANCE
FOR THE 500 MW BASE CASE SYSTEMS

	COLLECTOR EQUIPMENT			ASH REMOVAL EQUIPMENT		
		Maintenance ($/yr/10^{6}ft^2)			Maintenance ($/yr/10^{6}ft^2)	
Collector System	Operation ($/yr)	Material	Labor	Operation ($/yr)	Material	Labor
Hot-Side ESP	20,000	25,000	25,000	60,000	30,000	30,000
Cold-Side ESP (Am.)	20,000	25,000	25,000	60,000	10,000	10,000
Cold-Side ESP (Eur.)	20,000	15,000	15,000	60,000	10,000	10,000
Fabric Filter	20,000	*280,000	35,000	60,000	**8,000	**8,000

*This figure, estimated for two year bag replacement cycles, is approximately halved for four year bag replacement cycles.

**These figures increase to $15,000 per year per 10^{6}ft^2 for the 40 comparment system.

Maintenance figures were based on cost per 10^6 ft^2 of collection area per year. For fabric filters, maintenance costs were derived from costs due to scheduled and unscheduled bag replacements and additional maintenance. Bags were estimated at 90 ft^2 per bag and $40 per bag. Labor was based on $14 per hour for unscheduled replacements and $4 per hour for scheduled replacement. Unscheduled bag replacements were estimated to be 5 percent of total inventory per year, with labor based on one hour per bag replacement. Other maintenance was assumed to require 350 hours per year, with the cost of materials at the same rate as the cost of labor. These costs are summarized in Table 6.

TABLE 6

DETAILS OF BASE CASE
FABRIC FILTER COLLECTOR MAINTENANCE COSTS

	Maintenance Costs ($\$/yr/10^6 ft^2$)		
Type of Maintenance	Materials	Labor	Total
Scheduled bag replacement*	250,000	20,000	270,000
Unscheduled bag replacement	25,000	10,000	35,000
Additional Maintenance	5,000	5,000	10,000
Total	280,000	35,000	315,000

*Costs presented are for a two-year bag replacement cycle. If a four-year bag replacement cycle is assumed, costs decrease approximately 50%.

Power requirements were determined for each case. These include induced-draft and reverse-air fans, transformer-rectifier sets, hopper heaters, accessories (rappers, valves, compartment dampers, and ash removal equipment. Power requirement factors are shown in Table 7.

TABLE 7

BASE CASE POWER REQUIREMENTS

		Connected Power			
Collector	Collection Area ($10^6 ft^2$)	Reverse Air-Fans (kW)	Hopper Heaters (kW per hopper)	Accessories (kW per $10^6 ft^2$)	Ash Removal System (kW)
Hot Side ESP	1.056	0	0	300	500
Cold Side ESP (Am.)	0.691	0	10	300	500
Cold Side ESP (Eur.)	1.086	0	10	300	500
Fabric Filter	1.091	780	15	200	500

The power requirements for the transformer-rectifier sets were determined separately for each case from estimates of the current and voltage needed for each precipitator. A factor of 0.60 was used in the conversion of alternating to direct current. It was assumed that power connected to the sets would be double the maximum demand for power. For further details on the factors used to develop the estimated power requirements, see the detailed EPRI report.[1]

Annual operation and maintenance costs are presented in Figure 8. The trends are similar to the capital cost, but the fabric filters incur higher costs than the precipitators. Operating and maintenance costs were included for both the collectors and the ash removal equipment. The major operating cost was the consumption of electrical power. As expected, the frequency of bag replacement had a substantial effect on the maintenance costs for the fabric filters.

LEVELIZED COSTS

To compare the collectors, capital investment, operation and maintenance costs, and power requirements were combined and levelized over the 35-year life of the plant. For the economic analysis, the following factors were used:

Minimum acceptable return (MAR):	11%
Fixed charge rate (MAR, depreciation, insurance, and income on MAR):	16%
Interest during construction:	8.5%
Base year (Time zero):	1977
Escalation (fuel, operation and for materials and labor):	7%
Plant Capacity Factor:	0.70

The levelized costs for a 500 MW system, shown previously in Figure 1, represent the added or differential cost of power, in mills per kilowatt-hour, for particulate collection.

FINE PARTICLE EMISSIONS AND OPACITY

The outlet emission of particulates less than two microns in size were estimated by applying inlet size distributions of fly ash to fractional efficiencies for each particular case. Typical fractional efficiencies, shown in Figure 9, were tailored for collectors of different size through the use of a modified Deutsch relation.[2] By dividing both the inlet distribution and the fractional efficiency into particle size increments, an outlet size distribution was calculated for each case. This calculation is essentially a prediction of emissions less than two microns in aerodynamic diameter--the amount limited to 0.02 lb/10^6 Btu by New Mexico. For all cases, it was found that when emissions total less than 0.05 lb/10^6 Btu (the New Mexico limit for total particulate) the State's limit on sub-2-micron emissions was also met.

The observed opacity of a plume emitted from a power plant stack depends on a great number of variables, including the angle of the sun, wind direction, atmospheric conditions, and the qualifications of the observer. The measurement of opacity by an in-stack instrument reduces the variables to: grain loading; size distribution, shape, density, refractive index, and reflectance of the particle; stack diameter; and NO_x concentration.[3] Mathematical correlations based on these variables may be used to predict opacity, but the two most important parameters are grain loading and particle size distribution. Outlet particle size distributions were developed for each collector based on typical fractional efficiencies, rather than actual size measurements. The calculated opacities for precipitators were judged, on the basis of past experience, to be somewhat high. Upon investigation, it was found that the prediction of high opacity resulted from larger than expected concentration of fine particles. The high percentage of fines was a direct result of applying fractional efficiencies that were adjusted for each precipitator using the modified Deutsch relation. Based on considerable experience with existing installations, it was found that precipitators designed for the limit of 0.1 lb/10^6 Btu and meeting corresponding guarantees produced opacities of less than 20 percent. Combining this with the trends in the calculated opacities yielded Figure 10. The average curve shown in Figure 10 corresponds closely to good design emission limits--that is, precipitators designed for these limits will yield, during operation, approximately the opacities shown. For a design limit of 0.03 lb/10^6 Btu, opacities from 5 to 15 percent would be expected.

EQUIPMENT SELECTION PROCEDURE

The source of coal and the fly ash produced from burning that coal will have a major impact on the selection of particulate removal equipment. Within recent years, trends have developed that make the sizing of precipitators and fabric filters for continuous high performance more difficult. The four coals selected for the detailed EPRI study was an attempt to cover the major variation of coal and ash characteristics in the United States. But with new mines opening, both east and west, there are coals that are both better and worse for precipitators and fabric filters.

The Appalachian region production of high, medium, and low sulfur coals will make the decision extremely difficult between precipitators and fabric filters. Variation in precipitability of all coals from this region are well known. In general, precipitability is not strongly related to sulfur content as would normally be expected. Washing of the higher sulfur coals to remove sulfur (mainly as iron pyrite) will probably reduce the precipitability more than would be indicated by the percent of sulfur removed. The low precipitability of the low sulfur coals from this region is well known. Hot side precipitators have been used with varying success, depending mainly on the sodium content in the ash. Fabric filters need to be proven on the higher sulfur coals, but they should be considered on most medium and low sulfur Appalachian coals.

The East Central coal region (Illinois, Indiana, Iowa, Missouri, etc.) is a medium to high sulfur coal region, with very little low sulfur coal. These coals produce an ash that, in general, has a high precipitability, leading to reduced precipitator size and cost. Because of this fact, this region will probably see a higher percentage of precipitator installations than any other region in the United States.

The Northern Great Plains region (comprising North Dakota, South Dakota, Eastern Montana, and the Powder River Basin of Wyoming) contains a variety of coals, for which fly ash precipitability ranges from the highest to the lowest of any in the country. The high sodium, high moisture, and medium-low sufur North Dakota lignites are very easy to precipitate. The low sodium, low sulfur, and the medium moisture coals in the Powder River Basin may present major problems to precipitators because of the high restivity and high concentration of fine particulate. Fabric filters may have high pressure drop problems when handling the same Powder River Basin coal. However, additional experience is needed to accurately characterize the impact of these coals.

The low sulfur, low sodium coals in the Rocky Mountain region are difficult to precipitate, but the high sodium, low sulfur coals in this region will precipitate quite well. Existing fabric filters are performing very well with medium to low gas-side pressure drops and fabric filters will probably see extensive application on Rocky Mountain coals.

In order to determine what the appropriate device is for a specific application, the following plan might be considered:

1. Establish the coal to be burned over the life of the plant, if at all possible.

2. Define particulate characteristics (concentration, particle size, resistivity, etc.)

3. Determine efficiency required to meet all applicable regulations.

4. Size precipitator, selecting the appropriate SCA for guarantee performance, including redundancy for deterioration and other contingencies.

5. Size fabric filter in a similar manner.

6. Establish economics (capital cost, operating cost, maintenance cost, present worth or levelized annual costs).

7. Select the appropriate device (considering technical feasibility as outlined in Table 1, as well as bottom-line economics as developed in steps 1 through 6).

In developing comparative capital costs for the precipitator versus the fabric filter, it is extremely important to define all the components of the particulate removal system. Each device must be evaluated on a complete and comparable basis. In addition to the basic device itself, the additional costs that should be developed are for inlet and outlet ductwork, structural supports, duct insulation, dampers, expansion joints, turning vanes, foundations, ash handling equipment (up to a common transfer point), electrical power supply, hopper heaters, hopper ash level detectors, differential I.D. fan costs, fabric filter preheat and purge system if appropriate and erection costs. In the case of a hot side precipitator, the cost impact of air heater location and longer combustion air duct runs should be considered.

Careful attention must be paid to development of comparative operating and maintenance costs. Estimates of electrical power demand must be developed for the I.D. fan, transformer-rectifier sets, reverse air fans, hopper heaters, ash removal system and accessories, such as rappers, damper operators, purge and preheat systems, etc. The determination of precipitator transformer-rectifier (T-R) set power consumption can be a difficult number to establish. T-R set power consumption for high efficiency large SCA precipitators can be a significant value, almost exceeding the power difference in flue gas pressure drop between a precipitator and a fabric filter. Fabric filter bag life is another difficult area. Although the EPRI study used 2 year or 4 year bag lives, it is apparent from the fabric filter operating experience to date that bag lives of 3 to 4 years are common. In other words, the 2 year bag life may be too conservative.

Comprehensive and accurate maintenance data are difficult to obtain. The best sources for these data are the users; however, only a few utilities have kept accurate maintenance records. Typically, annual maintenance costs have been estimated as a small percentage (from 2 to 5%) of the original installed cost of the equipment.

DESIGN FOR RELIABILITY

The fact that no system can be expected to produce optimal results 100 percent of the time must be addressed in the design of a particulate collection system. For precipitators, clogged ash hoppers and broken wires are the biggest detriments to optimal performance.

For the fabric filter, the main difficulty is the premature failure of bags. As previously pointed out, operating experience with fabric filters has been much less than with precipitators, particularly for large coal-fired units and applications with high sulfur coal. Fabric filters now in operation on large low sulfur coal burning units will help to determine additional factors affecting reliability and operability.

For precipitators, since on-stream maintenance is not considered practical, additional bus sections are desireable to enable satisfactory performance until disabled sections can be repaired. Generally, utilities schedule a seven to ten day outage each year for minor maintenance. Major outages are scheduled every two or three years and can last 30 to 40 days. Since activity during unscheduled outages is very intense, only very high priority items are likely to receive attention. Thus, a well-designed precipitator should operate reliably at or above the efficiency corresponding to the emission limit for periods of a least one year without internal maintenance.

Degradation of precipitator performance can be minimized by increased electrical sectionalization. In recent installations, precipitators having as many as 100 independent electrical sections (bus sections) are not uncommon. In order to minimize the effect of an ash valve failure or plugged hopper, the trend is toward locating a hopper under each bus section. The reliability of a bus section depends on the design of the precipitator (e.g., rigid vs. weighted-wire electrode design), the ash-handling system, the abrasiveness of the dust, the degree of sparking encountered, and the temperature. Failure of weighted wire electrodes are usually concentrated in the inlet field where higher dust loadings cause more sparking and more abrasion. The use of the rigid electrodes has increased significantly because of this characteristic of the weighted wire electrode. Ash system failures can occur when a clinker of semi-fused fly ash falls into a hopper. The net result is that even a well designed precipitator may have 5 to 25 percent of the bus sections out of service by the end of a year. The loss in efficiency must be offset by additional collection area beyond the plate area added for performance efficiency contingencies. Commonly, this extra area is expressed in terms of extra fields. For instance, a precipitator that could meet guarantees with four fields may have a fifth field installed to account for normal deterioration and contingency. Occassionally, optimal contingencies are incorporated into the design, such as the addition of a sixth empty field. The plates and wires are installed in the sixth field only if performance proves to be unacceptable.

The reliability of a fabric filter system in meeting performance requirements is dependent mainly on the frequency of bag breakage, the time taken to isolate the broken bags, the leakage of bypass dampers, and sometimes the air-to-cloth ratio. Conservative design and proper operation can generally minimize the frequency of broken bags. Also, periodic replacement of all bags in a compartment will reduce the average age of the bags and the frequency of breakage. Minimizing excursions below the acid dew point also tends to extend bag life. The time to isolate a broken bag can be drastically reduced if detectors are placed on the outlet of each compartment. These detectors indicate the opacity of the gas stream at the individual compartment outlet, therby allowing the operators to quickly isolate the faulty compartment for repair. Leaks through bypass dampers also affect performance. The design used in the EPRI study incorporated two louvered dampers in series with a purge of clean reverse air to block uncleaned flue gas. High air-to-cloth ratios experienced during cleaning or maintenance can reduce performance. However, fabric filter efficiency generally is high enough that requirements can be met even during these periods. The air-to-cloth ratio influences reliability more strongly than performance because it affects bag life.

In contrast to a precipitator, dampers on the compartments of a fabric filter pose a possible restriction to the flow of gas from the boiler. As a result, controls must be designed so that it is essentially impossible for all compartment valves to close at once. As a back-up measure, the fabric filter bypass damper should be set to open automatically at high furnace pressure.

CONCLUSION

Stricter particulate emission standards have increased the costs for electrostatic precipitation, so that fabric filters have become cost competitive. Fabric filters remove submicron particles more thoroughly than do precipitators. However, there is much less operating experience with fabric filters than precipitators, particularly on large coal-fired units or applications with high sulfur coal. In general, the relative economic feasibility of well designed fabric filters and precipitators is dependent on the emission limitation, the ash and heating content of the coal, the properties of the ash, the bag replacement schedule for fabric filter, and site specific constraints. As a result of these considerations, the utility industry is comparing these two particulate collectors very carefully to determine the optimum choice.

REFERENCES

1. R.W. Scheck, S. D. Severson, et. al., "Economics of Fabric Filters Versus Precipitators," EPRI FP-775, June 1978.

2. S. Matts and P.Q. Ohnfeldt, "Efficient Gas Cleaning with S.F. Electrostatic Precipitators," SF Review, 1964.

3. D. S. Ensor, R. W. Scheck, et. al., "Fabric Filter Fractional Efficiency," EPRI FP-297, November 1976.

4. S. D. Severson, R. W. Scheck, et. al., "Economics of Fabric Filters Versus Precipitators," presented at the 86th National Meeting of the AICHE, Houston, Texas (April, 1979).

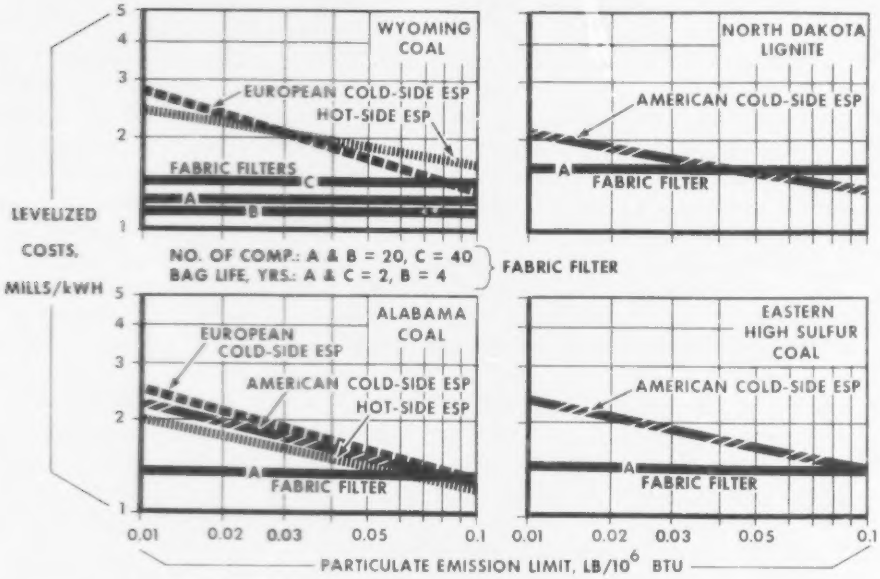

FIGURE 1
LEVELIZED COSTS FOR 500 MW COLLECTORS (1978)

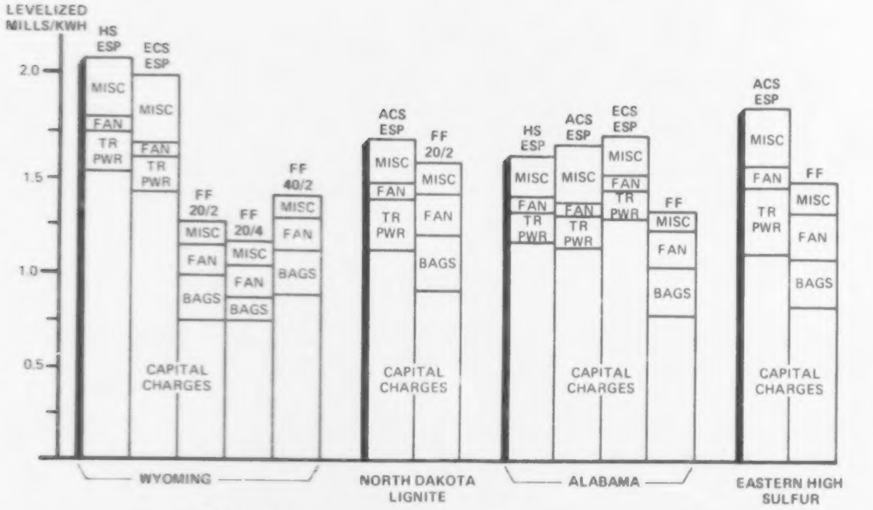

FIGURE 2

COMPONENTS OF COLLECTOR COST
AT THE 0.03 LB/10^6 BTU EMISSION LEVEL

KEY

HS ESP - HOT SIDE ELECTROSTATIC PRECIPITATOR
ACS - AMERICAN STYLE ESP
ECS - EUROPEAN STYLE ESP
FF - FABRIC FILTER
20/2 - 20 COMPARTMENTS, 2 YEAR BAG LIFE

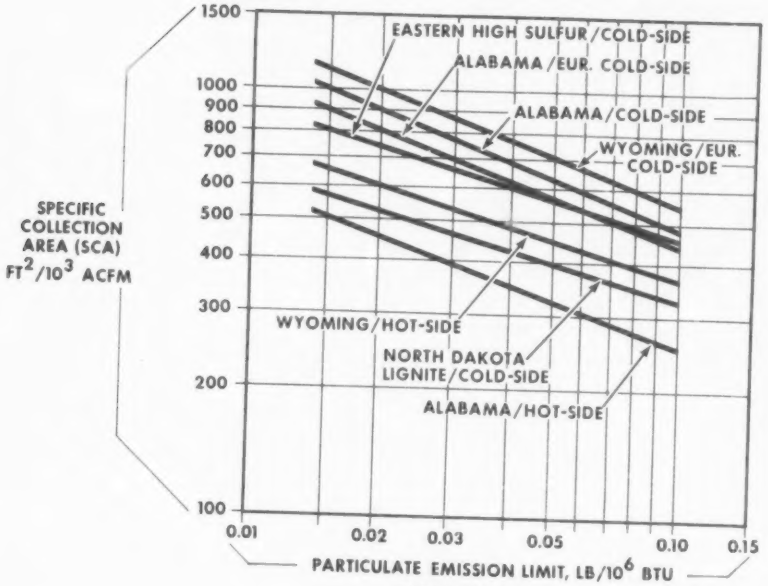

FIGURE 3
COLLECTING AREA REQUIREMENTS
FOR ELECTROSTATIC PRECIPITATORS

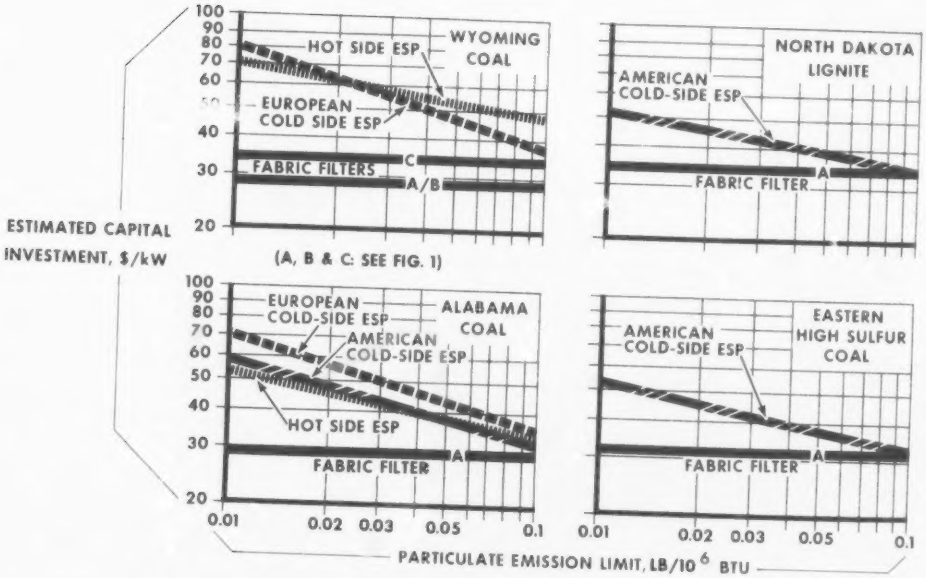

FIGURE 4
CAPITAL INVESTMENT FOR 500 MW COLLECTORS (1978)

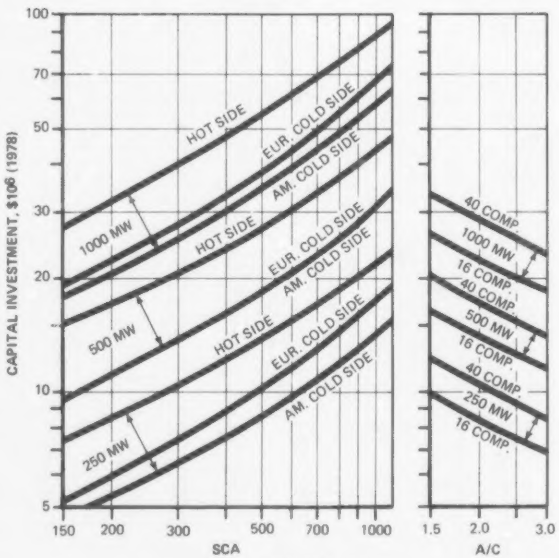

FIGURE 5

ESTIMATED CAPITAL INVESTMENT FOR COLLECTORS

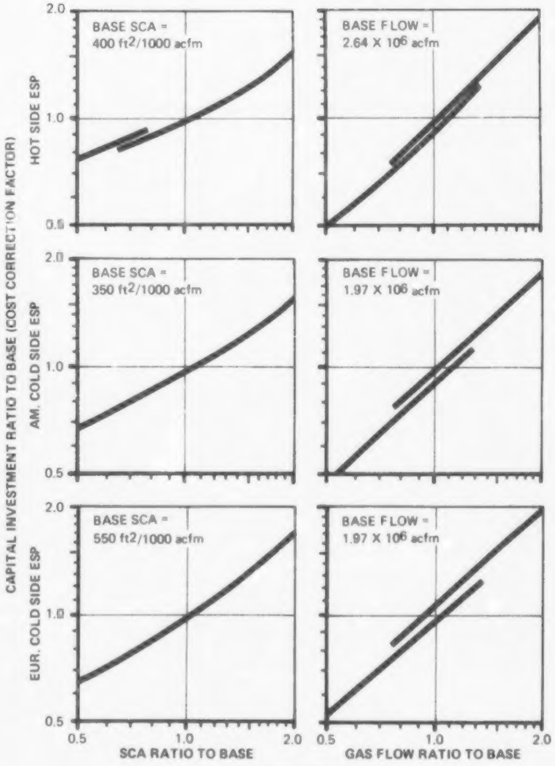

FIGURE 6

COST CORRECTION FACTORS FOR ELECTROSTATIC PRECIPITATORS

COST CORRECTION FACTORS ARE APPLIED TO THE CAPITAL INVESTMENT (CI) OF THE BASE CASE ESP SYSTEMS TO ARRIVE AT THE CI FOR THE CASE WITH A DIFFERENT DESIGN PARAMETER. FOR EXAMPLE, DOUBLING BOTH SCA AND GAS VOLUME ON A HOT SIDE ESP YIELDS A COST CORRECTION FACTOR OF 1.57 × 1.96 = 3.08. THIS FACTOR IS APPLIED TO THE CI OF THE BASE CASE HOT SIDE ESP SYSTEM ($23.9 × 10^6) TO ARRIVE AT THE CI OF THE NEW SYSTEM. DUAL LINES ON GRAPHS ON RIGHT RESULT FROM ORIENTATION CHANGES.

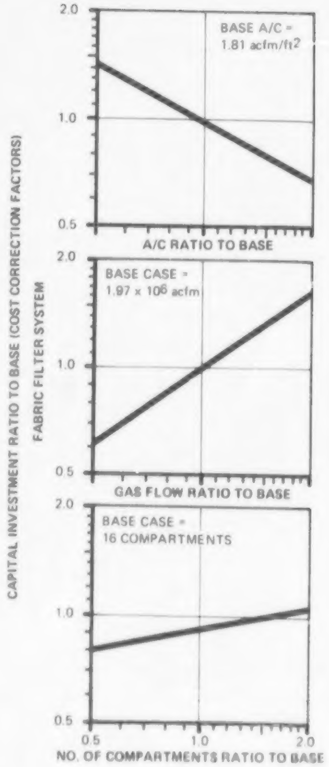

FIGURE 7

COST CORRECTION FACTORS FOR FABRIC FILTER

COST CORRECTION FACTORS ARE APPLIED TO THE CAPITAL INVESTMENT (CI) OF THE BASE CASE FABRIC FILTER SYSTEM TO ARRIVE AT THE CI FOR CASES WITH DIFFERENT DESIGN PARAMETERS. EXAMPLE: DOUBLING AIR TO CLOTH RATIO, GAS FLOW AND NUMBER OF COMPARTMENTS WILL YIELD A COST CORRECTION FACTOR OF $0.70 \times 1.65 = 1.36$. THIS FACTOR IS APPLIED TO THE CI OF THE BASE CASE FF SYSTEM ($\$14.59 \times 10^6$) TO ARRIVE AT THE CI OF THE NEW SYSTEM.

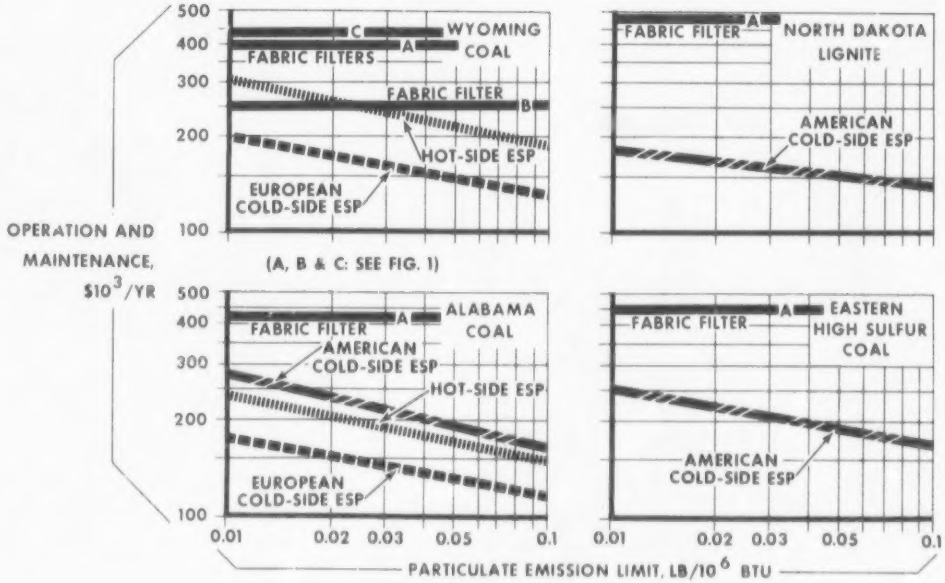

FIGURE 8

OPERATION AND MAINTENANCE COSTS FOR 500 MW COLLECTORS (1978)

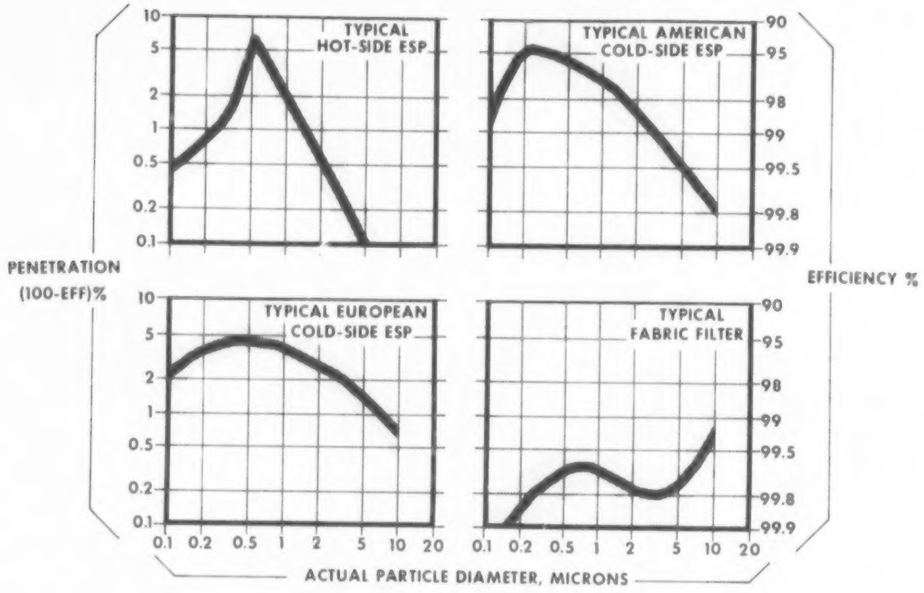

FIGURE 9
TYPICAL FRACTIONAL EFFICIENCIES FOR EXISTING COLLECTORS

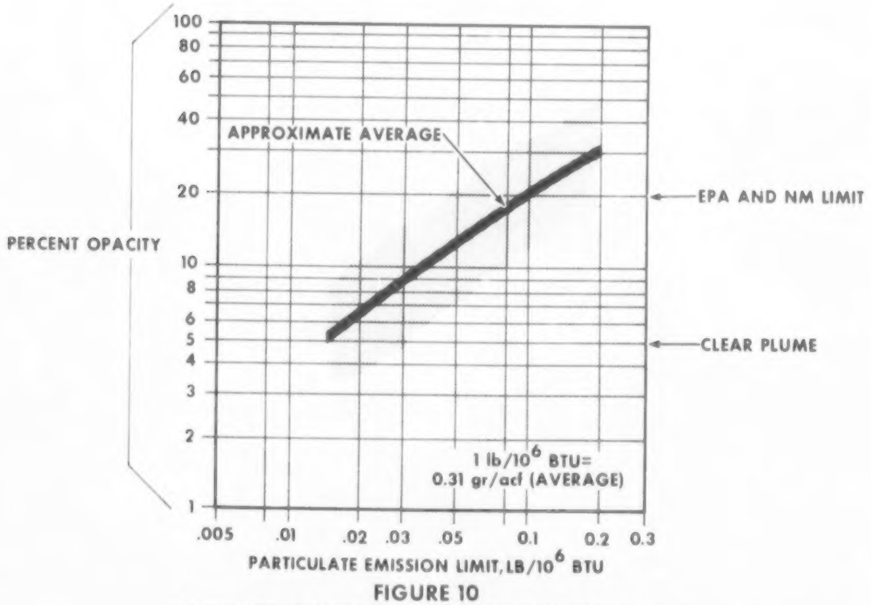

FIGURE 10
PREDICTED OPACITY VS. DESIGN EMISSION LIMIT
FOR PRECIPITATORS

DESIGN AND CONSTRUCTION OF BAGHOUSES FOR SHAWNEE STEAM PLANT

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ABSTRACT

This paper is a sequel to "Precipitators? Scrubbers? or Baghouses? for Shawnee" given at the first EPA symposium in 1978, which explained the basic reasons and philosophy for TVA's selection of baghouses for Shawnee.

In this presentation, the authors deal with the basic considerations of the specifications, detail design, and construction of the baghouse system for the 10-unit Shawnee Steam Plant. Special attention is given to a unique preheating and reheating system for each baghouse prior to boiler startup or for cycling operation, criteria for varying number of compartments online against flow (ACFM) to minimize dewpoint consideration, criteria of air-to-cloth ratio as well as filter material and coating, selection of materials, and construction of a unique raft foundation system--all within a total construction period of 42 months.

DESIGN AND CONSTRUCTION OF BAGHOUSES FOR SHAWNEE STEAM PLANT

INTRODUCTION AND GENERAL BACKGROUND

The Shawnee Steam Plant is located on the south bank of the Ohio River about 13 miles downstream from the mouth of the Tennessee River at Paducah, Kentucky. Construction of the ten 175-MW units was authorized in January 1951. Unit No. 1 was placed in commercial operation 27 months later in April 1953 and the last unit, No. 10, went into operation in October 1956, providing a total plant generating capacity of 1,750,000 kW at the total cost of $216,500,000 or $124 per kW.

(Based on today's costs for fossil plants, that sounds like a fairy tale, doesn't it!??)

The plant was first equipped with mechanical dust collectors primarily for induced-draft fan protection. Then in 1968, shortly after issuance of a Federal Executive Order in 1966, mandating increased pollution control TVA initiated a retrofit program for design and construction of electrostatic precipitators in order to comply with this order. This program of retrofitting ten units with 90 percent efficient electrostatic precipitators was completed in 1973 at a cost of $9,161,000. At that time, the flue gas was exiting into the ten stacks as seen here in this aerial photograph. (Show slide 1.) Then in 1974, in an effort to improve the ambient air quality and reduce local ground level concentrations of SO_2, a program of building two large 800-foot-high stacks was begun. These stacks were located 187 feet to the rear of the old stacks with long runs of ductwork connecting into a common breeching each one serving five units, as can be seen here in the photograph.

Since there was room for argument regarding our tall stack approach for control of SO_2, we also left room in the ductwork between the old stacks and new breeching for additional pollution abatement equipment if we lost our argument. In April of 1976, the Supreme Court ruled against tall stack control of SO_2, so we now had a chance to fill up this space of some 187 feet with something.

If we recap the chronology of air pollution project work at Shawnee, it shows up something like the illustration on slide 2.

Chronology of Air Pollution Projects

Program	Cost
1st Retrofit - Ten electrostatic precipitators at 90 percent efficiency - 1968-1973	$ 9,161,000
2nd Retrofit - Two 800-foot stacks, ductwork and breeching - 1974-1977	25,600,000
3rd and (Final)(?) Retrofit - Ten structural baghouses and all auxiliaries - 1978-1981	80,000,000
Total	$114,761,000
Total Plant Cost	$216,500,000
	or
	53 percent

Last year at this symposium, I presented a paper explaining the philosophy and economic advantages of why TVA chose a baghouse and low-sulfur coal in lieu of scrubbers as the solution. Today, we will try to explain the basic design criteria we have used in this baghouse installation.

TYPE OF CONTRACT AND SCOPE OF WORK

In considering the workload of our design and construction forces, it was decided that the Shawnee project should be done on a turnkey basis. Within this concept we would write specifications and take bids on the complete job of engineering, furnishing, and erection of equipment for the project. And so it was that on March 14, 1978, TVA awarded a contract to Buell Division of Envirotech Corporation in the amount of $53,218,000 for engineering, furnishing, and erecting ten baghouses and all auxiliaries as listed in the scope of work shown on slide 3.

Specification Outline

1. Structural Baghouse Fly Ash Collectors
2. Ductwork, Distribution Devices, Expansion Joints, and Louver Dampers
3. Insulation and Lagging
4. Fly Ash Handling Systems and Ash Sluice Water Piping
5. Washdown Pad Sump Pumps, Valves, Pipe, Hangers, Sewerage, and Freeze Protection
6. Induced-Draft Fans
7. Elevator and Hoists
8. Control Houses
9. Instruments and Control
10. Electrical Work

11. Structural Steel Supports and Miscellaneous Steel Access Platforms and Stairs
12. Concrete Foundations
13. Washdown Pads, Drains, and Sumps
14. Site Improvement, Parking Facilities, and Access Roads
15. Painting
16. Fire Protection

The next five slides (show slides 4, 5, 6, 7, and 8 of plans and elevations, pointing out various features) show the basic equipment layout and relationship to existing equipment. Significant man-hours have gone into the scheduling, design, procurement, and construction of the project to date. Last year little actual work had progressed at the project site; this year construction is well underway and the first unit is scheduled for tie-in in late fall. As can be seen from the slides there just is not ample room to spread out; equipment, laydown area, and workmen all are confined to the same general area. Scheduling the activities has been a difficult task.

SCHEDULE

The overall schedule, we believe, is very ambitious, and calls for completion of all ten units 42 months after award of contract. However, the industry did respond in a favorable manner; no one claimed the time was too short. Some of the major milestones for the schedule are shown on the bar chart here in slide 9.

Schedule

Program Schedule

TVA start specification	June 29, 1977
Purchasing issue invitation to bid	September 22, 1977
Bid opening	December 13, 1977
Award of contract	March 14, 1978
Start construction	April 24, 1978

Construction and Tie-In Schedule

Unit	Start Tie-In	Complete Tie-In
5	November 1, 1979	December 1, 1979
6	January 15, 1980	February 15, 1980
4	March 15, 1980	April 15, 1980
3	June 1, 1980	July 1, 1980
7	August 15, 1980	September 15, 1980
8	October 15, 1980	November 15, 1980
9	January 1, 1981	February 1, 1981
10	March 15, 1981	April 15, 1981
2	May 15, 1981	June 15, 1981
1	August 1, 1981	September 1, 1981

The contract provides for a bonus-penalty for early or late completion of the project. Since it is impossible as well as impractical to identify a precise cutoff date, we identified a 30-day dead band on each side of the complete construction date before bonus-penalty would be applied. On the 31st day, the bonus-penalty would accrue and continue until a maximum value of $500,000 was reached. The Contractor has recognized the potential for the bonus and from the very start has proceeded with the organization, design, schedule, and construction to capitalize on receiving the maximum bonus. All schedules and actions to date indicate they will complete the tie-in of the final unit early and earn a bonus.

SPECIFICATION REQUIREMENTS

In the spring of 1977 very few baghouses had been installed in utility plants and it certainly behooved us to take advantage of standing experience at that time. Therefore, in writing the specifications we had four objectives. They were:

1. Build on industry experience in adapting baghouses to utility boilers.
2. Specify a very conservative design (low differential pressure and air-to-cloth ratio [A/C]).
3. Stretch the industry's practice regarding bag life guarantees.
4. Incorporate and redefine TVA's broad precipitator experience into their first baghouse.

In short it was our intent to obtain equipment that would perform to the best available technology while providing ease of maintenance and at a competitive cost.

One major area of concern was the selection of the method of cleaning. Early in the project, we selected reverse air cleaning as the only type of cleaning method acceptable. This was not an accident or casual selection. As best could be determined, from the industry itself, it was the only method that had proven itself in utility operation. More experience had been collected on this cleaning method than any other and we felt that the Shawnee units should be given every opportunity to become a model design, not an experiment.

In slide 10 we see a summary of some detailed design criteria. (Show slide 10.)

Design Criteria

1. Coal - Either separately or blended eastern or western low-sulfur coal. Sulfur 0.33 percent. Moisture 30.2 percent. Ash 7.44 percent Heating value 8075 Btu/pound.
2. ACFM - Test block 650,000 with normal operation 585,000.
3. A/C - All compartments online at test block 2:1 (this will be explored later in the paper in great detail).
4. Bag - 11-7/8-inch diameter by 34-foot-7-3/4-inch 14-ounce fiberglass bag coated with teflon B finish, 9 percent by weight.

5. Cor-Ten for casing, hoppers, ductwork, and all gas contact surfaces.
6. Stainless steel bag hardware and poppet valve shafts and seals.
7. Dry fly ash handling system to pond and then wetted.
8. Fans, dampers, expansion joints, control houses, and related equipment necessary for the operation of the baghouse.
9. Each baghouse has ten compartments with 324 bags per compartment. Bags are arranged on 14-inch centers with 2-bag reach providing a grid of 12 by 27 (three walkways).

Well-designed equipment must be capable of being easily maintained. It was our intention, particularly since this was our first baghouse, to pay special attention to the ease of maintenance and especially to replacement of bags. I am well aware of the arguments regarding 2-bag versus 3-bag reach, but am not prepared to argue all the details and merits of one versus the other. We all know that Murphy's Law says "If something can go wrong it will." We could paraphrase that and say "If it is hard to maintain it won't be" or not often enough. Conversely, if you make it easy to fix or replace, chances are a lot better care will be taken of that particular feature. Pure and simple, this was the reason behind our decision to use a 2-bag reach in the design of the Shawnee baghouse. We believe that with ten units, 100 compartments, and 33,000 bags to watch after that anything to make maintenance or replacement easier is money well spent. One might ask "How much extra real estate or space does your 2-bag reach design take over the 3-bag reach?" The next slide indicates the difference in space. (Show slide 11.) There is only a 7 percent differential in the plan area and this only occurs in one direction. In our view this is "small potatoes" compared with the overall space required and of very little significance in extra money spent for 2-bag versus 3-bag reach. As a result of this, our 2-bag reach decision was really an easy one.

AIR-TO-CLOTH RATIO CRITERIA

As most of you know who have tried to size dust collectors, obtaining a consistent story of how much cloth area is in a bag is not an easy task. To keep all bidders on an equal footing, we were very specific on how to determine active cloth area. The calculating of active cloth area is no art; it is just important that all bidders understand and calculate the active cloth area in the same manner. As a guide, I have included how we calculated active cloth area. (Show slide 12.) On the left you will see a typical bag configuration and just to the right of it is a flat cloth layout of the same bag. Our approach was to use the overall cloth area and deduct the top cuff, vertical seam, anticollapse ring seams, and bottom cuff seam areas. The overall cloth area is 107.71 square feet and with the deductions this reduces to 102.47 square feet. On the extreme right-hand side of the slide is a summary of the cloth area per bag, per compartment, and per collector. There is only 5.24 square feet differential area per bag, but this equates to 16,977 square feet per collector. Significant advantages or disadvantages could be given to a potential bidder if all bidders were not calculating cloth area in the same manner. This is by no means the only approach, and I do not intend to pretend other approaches are not acceptable. It is our method and we believe indicates a conservative approach.

As a followup to calculating cloth area, we think the definition and calculation of air-to-cloth ratios is equally important. (Show slide 13.)

AIR-TO-CLOTH RATIO

BASED ON ACTIVE CLOTH AREA (102.47 SQUARE FEET/BAG)

	Test Block (Excluding Reverse Air) 650,000 ACFM	Test Block (Including Reverse Air) 708,000 ACFM	Normal Operation (Excluding Reverse Air) 585,000 ACFM	Normal Operation (Including Reverse Air) 643,000 ACFM
All compartments online (10)	1.96	*	1.76	*
One compartment down for cleaning (9)	2.18	2.37	1.96	2.15
One compartment down for cleaning and one down for maintenance (8)	2.45	2.67	2.20	2.42

*Reverse air is not on when ten compartments are filtering.

As can be seen in the slide, it is easy to get confused when talking A/C ratios, and it is important to know the basis when you talk A/C ratios. You can see that while a 2 to 1 ratio is referred to, it is more or less nominal and the real operating condition which the baghouse uses is a more conservative 1.76 to 1.

The arrows indicate the normal conditions of service that the baghouse will see. The air-to-cloth ratio changes from 1.76 to 2.15 (for cleaning) to 2.42 (for cleaning and maintenance). We feel this is consistent with our conservative approach of providing low maintenance by designing for longevity of bag life due to low differential pressure. The additional capital cost for a larger dust collector is easily written off when compared to the subsequent capitol and maintenance cost of high-pressure drop and more frequent bag maintenance. The increase in incremental capitol cost for lower air-to-cloth ratios is relatively insignificant compared to the cost of replacement power.

Our philosophy of conservative air-to-cloth ratio and resultant low-pressure drop paid off in a suprising bonus. The successful bidder offered a 3-year bag life guarantee rather than the 2-year as specified. This extra year of guarantee we feel is the type response that the pollution abatement equipment suppliers must extend to the utility industry. Last year I challenged the industry itself that "its success depends upon the industry's response to new applications of an old technology." We at TVA were glad to see that not only Envirotech but the industry took steps in a responsive direction. The extra year of bag life guarantee equates directly to savings in loss of power generation. Shawnee is a base load station and as such must run relatively loaded all the time. The utilization rate for Shawnee is the highest in the system and runs around 90 percent. Anything that can be done to reduce maintenance will result in savings over the long haul and help hold the cost of electricity as low as possible.

GUARANTEES

The next slide highlights a few of the performance and guarantee data that was required by the specifications and offered by Envirotech. (Show slide 14.)

Performance and Guarantee Data

	Specification Requirement	Envirotech Offered
Maximum allowable outlet grain loading (grain/ACF)	0.005	0.005
Maximum allowable pressure drop (inches of water)	6-3/4	5-7/8
Fabric filter bag life (years)	2	3

As can be seen, Envirotech offered the same outlet grain loading while improving on pressure drop and bag life guarantees as defined in the invitation.

I said earlier that one of our objectives was to stretch the industry's practice regarding bag life guarantees. We did not expect that a Contractor would go us one better by offering 1 extra year bag life than we specified and 7/8-inch less pressure drop. Needless to say we were pleased with this response, particularly since it was in the two most difficult and important areas of the specification requirements. These guarantees offered by the contractor represent hundreds of thousands of dollars if not attained and we know they were not taken lightly by the contractor.

Again we feel that this type of response on the part of the industry is a necessary step for baghouse supplier's to take in order to participate in particulate control for utility applications.

DESIGN SCHEMATIC

The fabric filter baghouse system, as furnished by the contractor, receives a total of 6,500,000 ACFM of flue gases from twenty air preheaters (two for each boiler) at 325° F, processes this volume of flue gases through ten fabric filters and exits at 0.005 grain/ACF. Each of the ten fabric filters serve one pulverized coal-fired reheat unit of radiant type, natural circulation. Each fabric filter will be placed downstream of an existing deenergized precipitator. The fabric filters, as furnished by the contractor, are capable of being operated immediately upon startup of each boiler, without adversely affecting operation of the baghouse through the employment of a uniquely designed warm air preheat system.

Immediately upon leaving the two deenergized precipitators, the flue gases travel through air preheater pressure equalizing louver-type dampers. These dampers are interlocked with the boiler logic and they also act to balance the load on the boiler. The damper blades are of airfoil design, stiffened as necessary, have no external ribs, and have built-in provisions to accommodate the thermal expansion between the blades and the damper frame proper.

At the inlet area of each of the ten fabric filters are six poppet-type bypass dampers. (Show slide 15.) The filter bypass poppet valves (three of which are shown) are activated automatically due to overpressure, excessive temperature, and low temperature; and manually for the maintenance of an entire unit. With the bypass dampers in the bypass mode or position, the differential pressure across the system is not allowed to vary by more than 2 inches from normal, with fabric filter online, in order to prevent boiler unbalances associated with significant changes in flue gas pressures. During normal filtering mode all six bypass poppet valves are closed.

As the flue gases leave the bypass area, they begin their travel to the fabric filter through the inlet manifold fabricated of 1/4-inch-thick Cor-Ten A steel plate. It should be noted that all ducts are designed to support a 1-foot depth of 75 pounds per cubic foot of fly ash. Quick-opening access and inspection doors, as well as appropriate turning vanes, are provided throughout the ductwork system.

(Show slide 16.) To enter each of the ten fabric filter compartments, the flue gases must pass through inlet poppet dampers of a metal-to-metal positive seal design. There are twenty of these dampers for each fabric filter, and they normally remain in the open position, except when a compartment is down for maintenance or inspection and bypass, in which case the inlet poppet dampers (two per compartment) are closed for complete isolation of flue gases. When a boiler is operating on reduced load, there will be a lower flue gas volume and a lower gas temperature. During these periods (especially when a boiler is in a cycling mode) baghouse compartments can be isolated to reduce the total cloth area (that is, to keep the A/C ratio close to 2:1) and exposed steel surfaces to the flue gas. This will accomplish two key objectives: (1) It will reduce loading and unloading of the filter cloth and should extend over all bag life and (2) it will reduce the heat sink (large amount of metal surfaces in contact with gas) that would decrease even further the gas temperature and help to maintain temperature above the dewpoint. If all ten compartments are offline for any reason, all twenty inlet poppet dampers would be placed in the closed position. The dampers are heavy duty air-cylinder driven, and are designed such that the normal flow of the flue gas aids in establishing a seal. In addition to the twenty poppet-type inlet dampers, there are twenty similar design outlet and reverse air dampers. (Show slide 17.) The outlet and reverse air dampers are continuously used in the continual process of sequentially operating and cleaning the fabric filter compartments. When a compartment is down for maintenance all inlet, outlet, and reverse air poppet dampers providing flue gas to that compartment are in tight closed, sealed position. (Show slide 18.)

A purge air system is also incorporated in the fabric filter design to assist in the rapid cooling down of any compartment which is brought offline for maintenance, while the adjacent compartments remain online. To accomplish this task, the contractor has included one vaneaxial fan per fabric filter.

The exact design of the ductwork and fabric filter equipment distribution devices were identified and incorporated as a result of an extensive model study of the total system conducted by the contractor. The contractor constructed a 1/4-inch 3-dimensional scale model of the fabric filters and of that portion of ductwork that was necessary to perform tests to minimize fly ash fallout and provide uniform flue gas and temperature distribution through the fabric filters and associated ductwork. (Show slides 19, 20, and 21.)

These photographs of the model show turning vanes and gas distribution devices that were added to aid in the reduction of pressure losses. Good gasflow distribution in some places was only obtainable through the use of gas distribution devices. An example of this is obtaining even gasflow across the grid sheet. (Show slide 22.) The flue gas entering the individual hoppers from the two inlets passes across a baffle or deflector plate, which has the effect of equally distributing the flue gases to all bags within the individual compartments. The hopper flow deflector will aid in the evening of particulate concentrations across all the cloth in the compartment and this should result in reducing localized bag failure. Without this deflector plate the flue gas tended to turn immediately upwards through the tube sheet and not flow across to the far side as indicated in this slide.

It may be the opinion of some that good gasflow distribution is necessary only for precipitators. This was basically our "gut feel" at the start but since this was our first baghouse we felt we would go ahead and model test--"it couldn't hurt anything." Now we are glad we did. Based on the improvements in gasflow, reduction of pressure drop, and all we learned from this model test, we would have to say "it is just as important and beneficial to model test a baghouse as it is a precipitator."

In order to provide delivery power for the flue gases from the air preheater through the base of the two 800-foot stacks, two induced-draft fans per fabric filter are provided. Each of the induced-draft fans are double inlet, double width units. The two fans per boiler will normally be started and run together. The test block requirements for each induced-draft fan is 354,000 ACFM at 325° F, with a fan static pressure of 31.5 inches wg at the inlet, and 0 inch wg static pressure at the outlet of the fan. The blades of the induced-draft fans are of the airfoil type. The fans have direct connected 2000-hp motors, operate at 900 rpm, and have inlet louver dampers for isolation. The fans also have conical variable inlet vanes for inlet volume control and to provide pressure balancing for the fabric filter and boiler operation.

(Show slide 23.) The most unique feature of the entire baghouse installation is the reverse air cleaning and prewarming system.

The induced-draft fans are the principal mode of fabric filter reverse air cleaning with the reverse air fans being provided for backup cleaning during periods of excessive pressure drop or other unusual conditions. As such, the induced-draft fans can be subjected to variations in pressure of up to ±1 inch wg every 5 minutes and having a duration of some 30 seconds. The induced-draft fans, dampers, actuators, and controls have been selected for this duty. There is a total of ten reverse air fans (one for each fabric filter). The compartment warming system utilizes the reverse air system to preheat offstream compartments or an entire baghouse with cleaned, heated flue gas from the outlet breeching.

Referring to the slide and as noted before there are five baghouses connected to each breeching and stack. Thus, there is always a constant source of clean, heated flue gas to be used for reverse air cleaning or prewarming a compartment or baghouse. Here is how it works: The pressure in the stack breeching is approximately 0 to +1 inch H_2O and the pressure at the inlet to the baghouse is approximately -20 inches H_2O. To initiate cleaning, all that is required is to open the appropriate damper, bypassing the reverse air fan, and clean hot gas will flow to the desired compartment. As long as an induced-draft fan is running, it may never be necessary to use the reverse air fan. The reverse air fans will be used if pressure upset conditions should occur or to preheat offstream compartments when the induced-draft fans are out of service (an example would be on cold startup). To ensure that the bags are not subjected to violent pressure changes during cleaning or warming, a modulating reverse air damper will control and maintain a constant flow, thus providing a constant A/C ratio when cleaning. We believe the real advantage of this system is the ability to prewarm any baghouse prior to its receiving gas from the boiler. We can avoid shocking a cold baghouse with 325° F dust-laden gas without a costly steam or other type preheating system.

QUALITY ASSURANCE PROGRAM FOR BAGS

The quality control program which the contractor established in cooperation with the bag vendor for the manufacture of the TVA filter bags is necessary to ensure the bags are manufactured to the customer specifications. (Show slide 24.)

Fabric Filter Quality Assurance Program

1. Bag hardware: Inspected at 10 percent random sample minimum, includes weld strength tests on anticollapse rings.
2. Fabric: In-house fiberglass rolls are inspected 100 percent for roll numbers, lot numbers, and test certifications.
3. Thread: Tested for strength, plies, and compliance to specifications.
4. Equipment: Machines are inspected for proper operation and function, including layout table marks.
5. Fabrication: Workmanship is checked at all work stations: layout, seaming, ringing, cuffing, packaging. Cloth condition is inspected at each work station.

The program provides the bag vendor with the ability to trace all raw materials used during manufacture back to the original supplier, and due to various inspections and certifications also ensures that these raw materials meet the specifications as required by TVA.

The quality assurance program provides methods of inspection whereby all hardware and fabric items are checked for proper sizing, as well as material type specifications. The program stipulates work in process quality control checks be made at the different manufacturing stations for cutting, seaming, cuffing, and ringing. (Show slide 25.)

Filter Cloth Test Certifications

Test	Method
Weight	ASTM D 1910
Thickness	ASTM D 1777
Count*	ASTM D 1910
Permeability	ASTM D 737
Tensile strength*	ASTM 1682, Method IR-T
Mullen burst	ASTM D 231
Mit flex	
Organic content	ASTM D 578
Water repellancy	ASTM D 2721
Yarn weight	ASTM D 578
Yarn twist*	ASTM D 578
Microscopic exam*	

*Warp and fill

After manufacture, each individual bag is then checked for size and any defects before being individually packaged.

The contractor as well as the bag vendor believes in quality; the quality assurance program is the tool used to enable them to purchase the raw materials and produce some 35,000 quality filter bags.

This quality control program, coupled with the conservative air-to-cloth ratio and low pressure drop and the specification requirement of 14-ounce-per-square-yard cloth, was the main consideration in the contractor's decision to offer a 3-year bag life guarantee.

INSTRUMENTATION AND CONTROLS

The Shawnee baghouse has been equipped with a full complement of alarms, annunicators, monitors, and strip chart recorders in order that the control room operator can monitor and operate the baghouses. Dual monitoring controls are provided in the unit control room and baghouse control room. Depending on the type of maintenance and/or operation, the appropriate control panels can be selected to perform the activity.

Display boards, mimic panels, lights, and status indicators add much needed useful information to the operators. The approach for design has been to make available to the main control room operator controls of the level and type necessary for the operation of the baghouse in conjunction with the boiler. At a glance the control room operator can determine the mode of cleaning operation, baghouse pressure differential, inlet and outlet flue gas temperatures, reverse air temperature, status of compartments (whether filtering, cleaning, or maintenance) system draft, various system failures, or other key operational inputs. Envirotech and TVA have worked closely to identify and provide the instrumentation, controls, and boiler interlocks necessary for the operation of the boiler, turbine generator, and baghouse as an integrated system.

CONSTRUCTION

There were two schemes considered for constructing the ten baghouses. One was to start at one end and work towards the other end in progression. However, after completing the schedule for this scheme it was decided we should try to find a way to complete the job in a shorter time frame. As a result we struck upon the scheme now being used of starting at the center on units 5 by 6 simultaneously and working out towards each end at the same time. This scheme permitted the use of two cranes simultaneously and more efficient scheduling and use of manpower. (Show slide 26.)

One of the most unusual construction features of this project is the foundation. Because of the high water table and soil characteristics, it was necessary to design and build a raft or bathtub type foundation which would float. The floor of this bathtub foundation for all ten units is 100 feet wide, 825 feet long, and 3 feet thick. The walls are 13-1/2 feet high and 1-1/2 feet thick around the entire perimeter. A grid work of steel support columns is erected inside this bathtub to support decking, over which is poured a washdown slab as a roof over the bathtub at grade level. (Show slide 27.) The baghouses are then erected above this grade level roof over the bathtub foundation starting in the center and working outwards to both ends simultaneously. At the present, construction is proceeding ahead of schedule and from all indication it appears the contractor will be ready for an earlier tie-in than called for in the schedule. (Show slides 28, 29, 30, 31, 32, 33, and 34.)

SUMMARY

When we announced our decision to install ten baghouses at Shawnee two years ago, we were certainly aware of the pioneering nature of the magnitude of this decision. I shall never forget the question put to me by Ed Stenby of Stearns Rogers when he asked incredulously "Al, you are putting in ten baghouses? You're not going to put in one and try it out"? I have explained before that we did not have the luxury of that option, sensible as it is. We had to commit all ten units to particulate control, but believe me that question had its impact on our thinking. If we made a mistake, it would happen ten times in whatever area of design we were in!!

As a result our goal has been to design a conservative baghouse system. There has been no attempt at any stage of design to cut corners or economize at the expense of quality. TVA and the contractor, Envirotech, have recognized the importance of conservatism and quality in design from the beginning of this project. The spirit of cooperation could not be better, and the turnkey concept has proven to be a satisfactory one.

Late this year at Shawnee No. 5, TVA will start up the first baghouse ever in its system to be followed at approximately 2-month intervals by nine more. We do not expect that this startup will be trouble-free--nothing ever is. However, because of conservatism in design, special attention paid to all details and desire to do a good job on the part of the contractor, we believe after initial shakedown that the Shawnee plant will be living testimony to the fact that baghouses can be a viable alternative to successfully collect particulates in large, multiunit central electric generating stations.

CHRONOLOGY OF AIR POLLUTION PROJECTS
UNITS 1-10
SHAWNEE STEAM PLANT

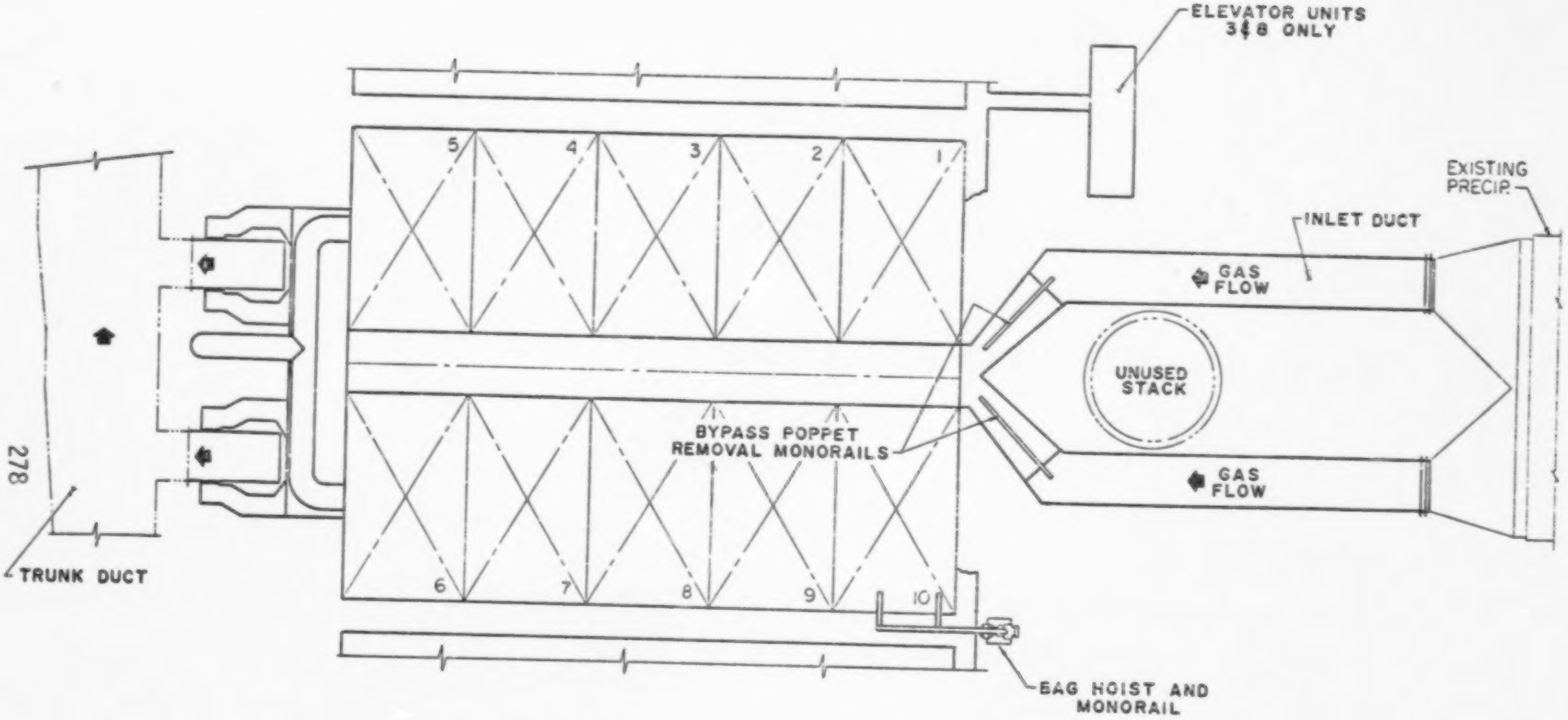
PROGRAM	COST
1ST RETROFIT - 10 ELECTROSTATIC PRECIPITATORS AT 90-% EFFICIENCY - 1968-1973	$ 9,161,000
2ND RETROFIT - TWO 800-FOOT STACKS, DUCTOWRK, AND BREECHING - 1974-1977	25,600,000
3RD AND (FINAL)(?) RETROFIT - 10 STRUCTURAL BAGHOUSES AND ALL AUXILIARIES - 1978-1981	80,000,000
TOTAL	$114,761,000 --53% TOTAL PLANT COST
TOTAL PLANT COST	$216,500,000

SLIDE NO. 2

STRUCTURAL BAGHOUSE
SHAWNEE STEAM PLANT
UNITS 1-10

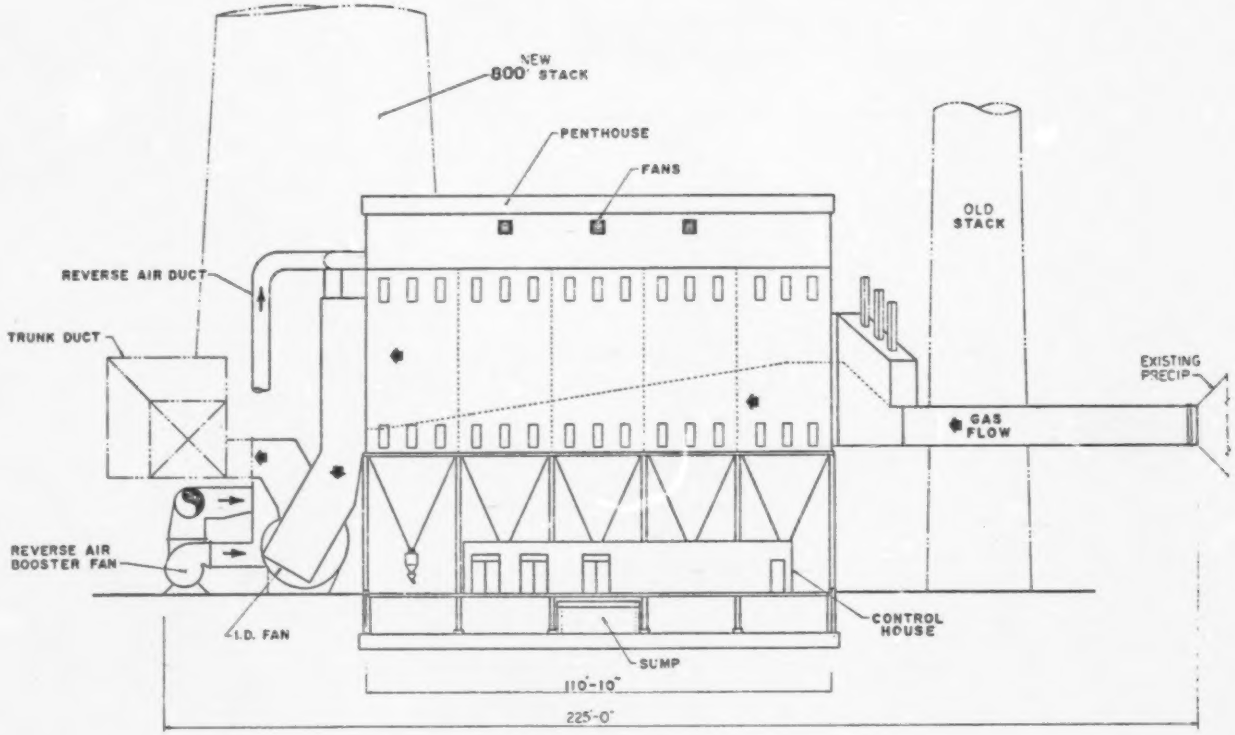
SPECIFICATION OUTLINE

1. STRUCTURAL BAGHOUSE FLY ASH COLLECTORS
2. DUCTWORK, DISTRIBUTION DEVICES, EXPANSION JOINTS, AND LOUVER DAMPERS
3. INSULATION AND LAGGING
4. FLY ASH HANDLING SYSTEMS AND ASH SLUICE WATER PIPING
5. WASHDOWN PAD SUMP PUMPS, VALVES, PIPE, HANGERS, SEWERAGE, AND FREEZE PROTECTION
6. INDUCED-DRAFT FANS
7. ELEVATOR AND HOISTS
8. CONTROL HOUSES
9. INSTRUMENTS AND CONTROL
10. ELECTRICAL WORK
11. STRUCTURAL STEEL SUPPORTS AND MISCELLANEOUS STEEL ACCESS PLATFORMS AND STAIRS
12. CONCRETE FOUNDATIONS
13. WASHDOWN PADS, DRAINS, AND SUMPS
14. SITE IMPROVEMENT, PARKING FACILITIES, AND ACCESS ROADS
15. PAINTING
16. FIRE PROTECTION



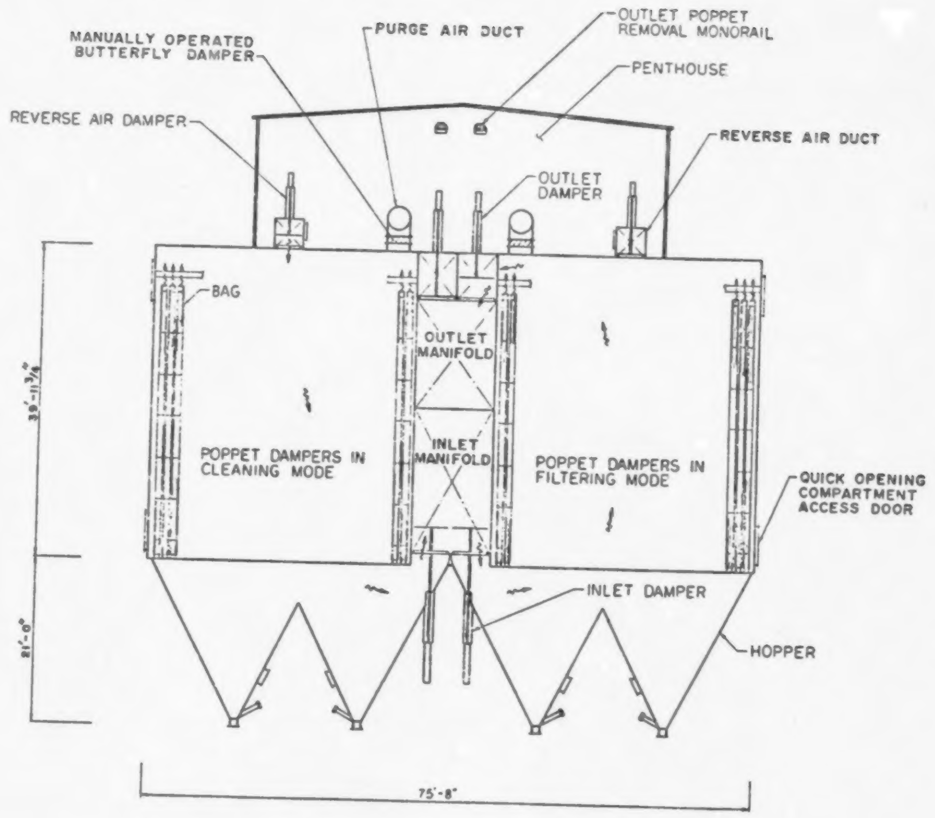
BAGHOUSE
PLAN VIEW

SLIDE NO. 4



BAGHOUSE
WEST WALL ELEVATION

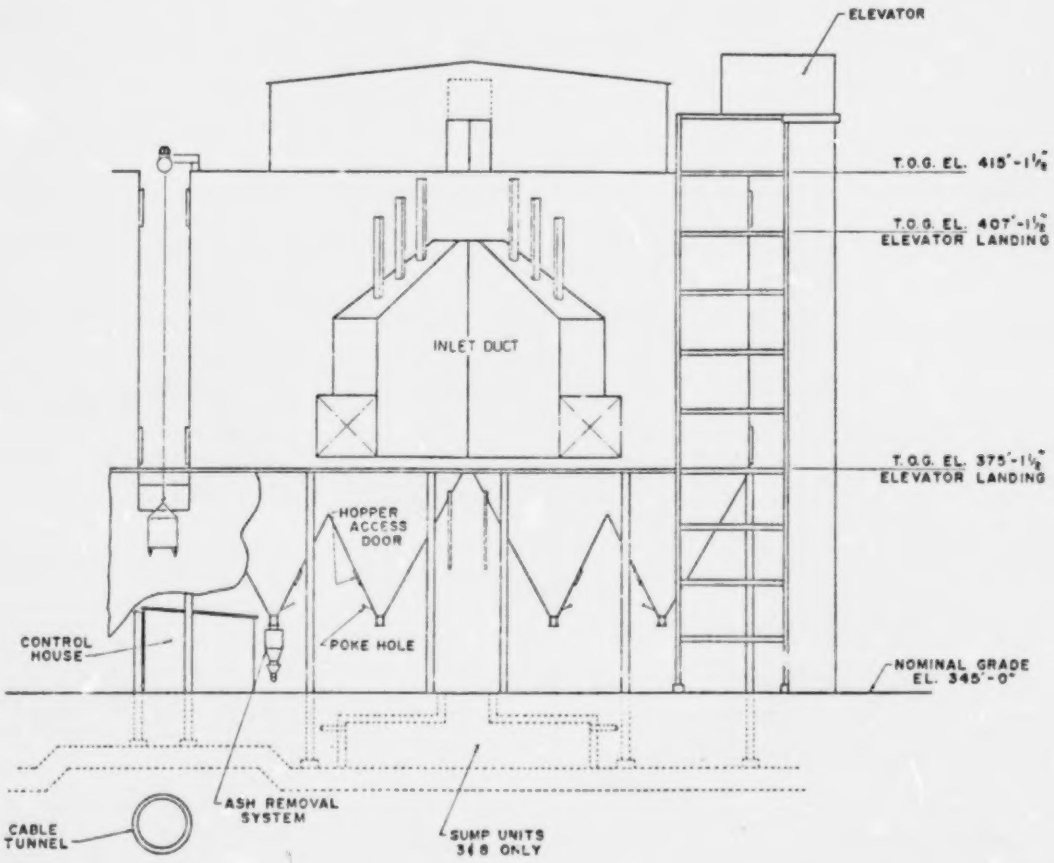
SLIDE NO. 5



MANUALLY OPERATED BUTTERFLY DAMPER
PURGE AIR DUCT
OUTLET POPPET REMOVAL MONORAIL
PENTHOUSE
REVERSE AIR DAMPER
REVERSE AIR DUCT
OUTLET DAMPER
BAG
OUTLET MANIFOLD
INLET MANIFOLD
POPPET DAMPERS IN CLEANING MODE
POPPET DAMPERS IN FILTERING MODE
QUICK OPENING COMPARTMENT ACCESS DOOR
INLET DAMPER
HOPPER
39'-11 3/4"
21'-0"
75'-8"

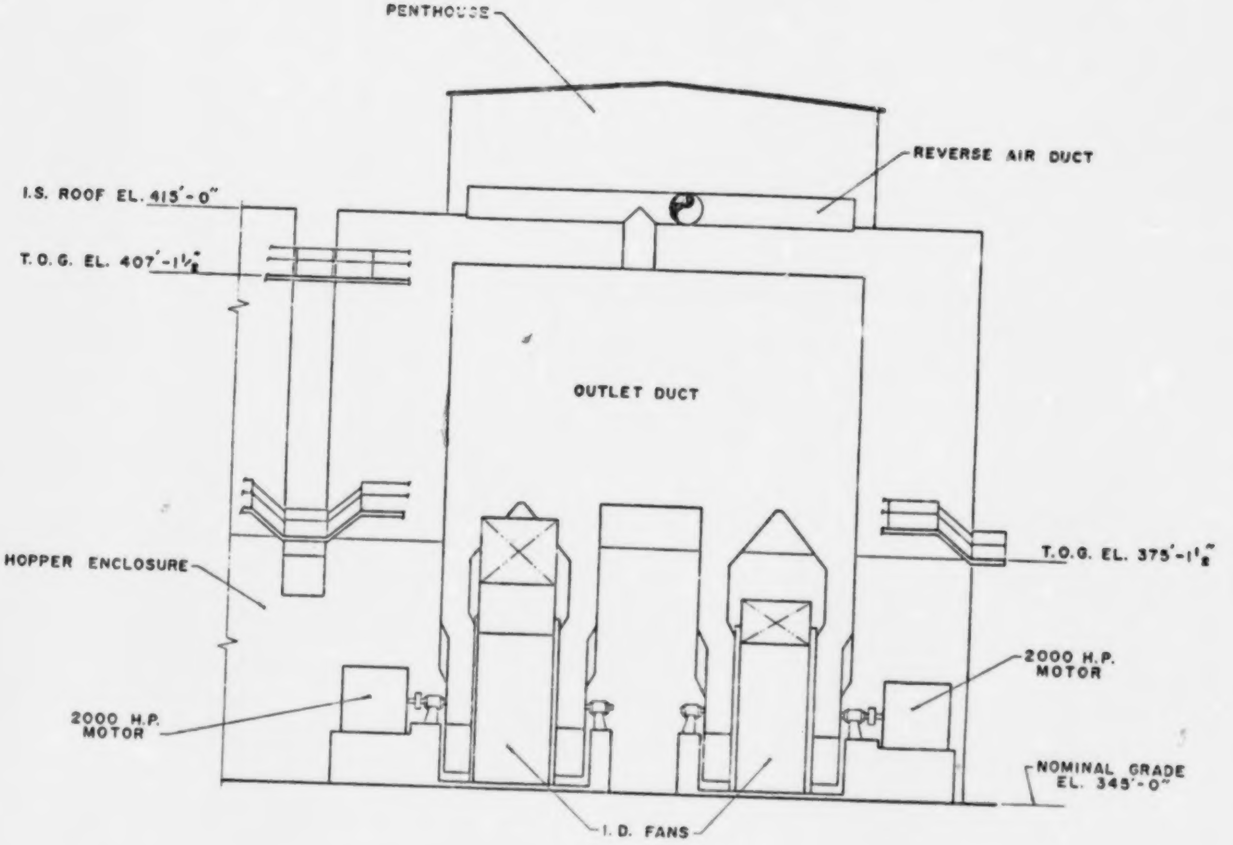
BAGHOUSE
SECTIONAL VIEW

SLIDE NO. 6



BAGHOUSE
SOUTH WALL ELEVATION

SLIDE NO. 7



SLIDE NO. 8

BAGHOUSE
NORTH WALL ELEVATION

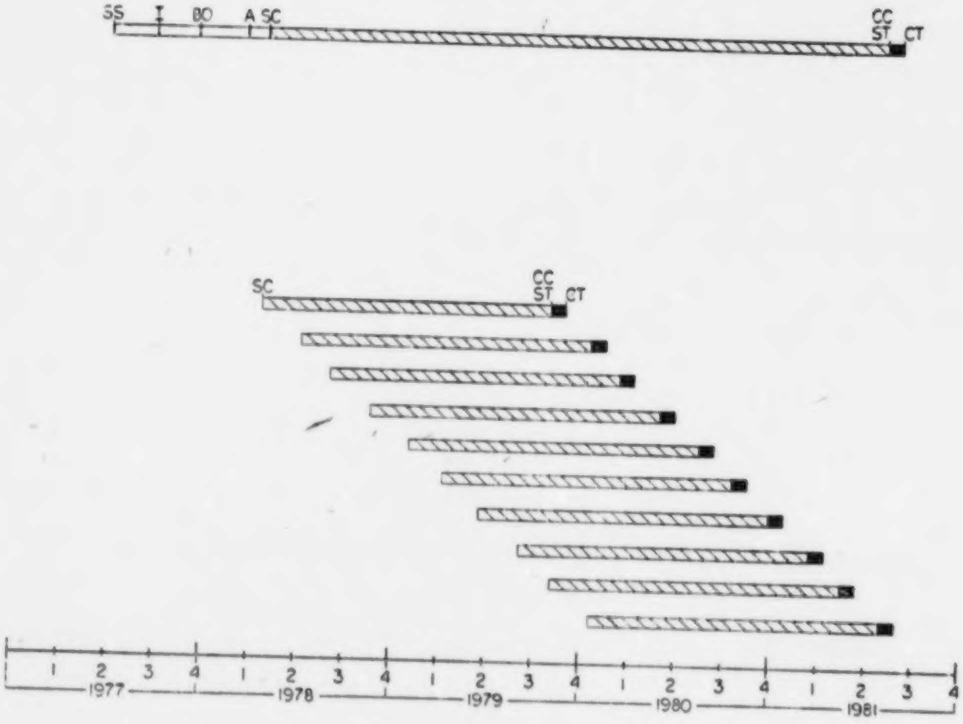
PROGRAM SCHEDULE

TVA START SPECIFICATION	JUNE 29, 1977
PURCHASING ISSUE INVITATION TO BID	SEPTEMBER 22, 1977
BID OPENING	DECEMBER 13, 1977
AWARD OF CONTRACT	MARCH 14, 1978
START CONSTRUCTION	APRIL 24, 1978

CONSTRUCTION AND TIE-IN SCHEDULE

UNIT	START TIE-IN	COMPLETE TIE-IN
5	NOVEMBER 1, 1979	DECEMBER 1, 1979
6	JANUARY 15, 1980	FEBRUARY 15, 1980
4	MARCH 15, 1980	APRIL 15, 1980
3	JUNE 1, 1980	JULY 1, 1980
7	AUGUST 15, 1980	SEPTEMBER 15, 1980
8	OCTOBER 15, 1980	NOVEMBER 15, 1980
9	JANUARY 1, 1981	FEBRUARY 1, 1981
10	MARCH 15, 1981	APRIL 15, 1981
2	MAY 15, 1981	JUNE 15, 1981
1	AUGUST 1, 1981	SEPTEMBER 1, 1981

SCHEDULE
SHAWNEE STEAM PLANT UNITS 1-10
STRUCTURAL BAGHOUSE FLY ASH COLLECTORS
TVA - ENVIROTECH



LEGEND
- ▨ - CONSTRUCTION
- ■ - TIE-IN
- SS - START SPECIFICATION
- I - ISSUE INVITATION
- BO - BID OPENING
- A - AWARD
- SC - START CONSTRUCTION
- CC - COMPLETE CONSTRUCTION
- ST - START TIE-IN
- CT - COMPLETE TIE-IN

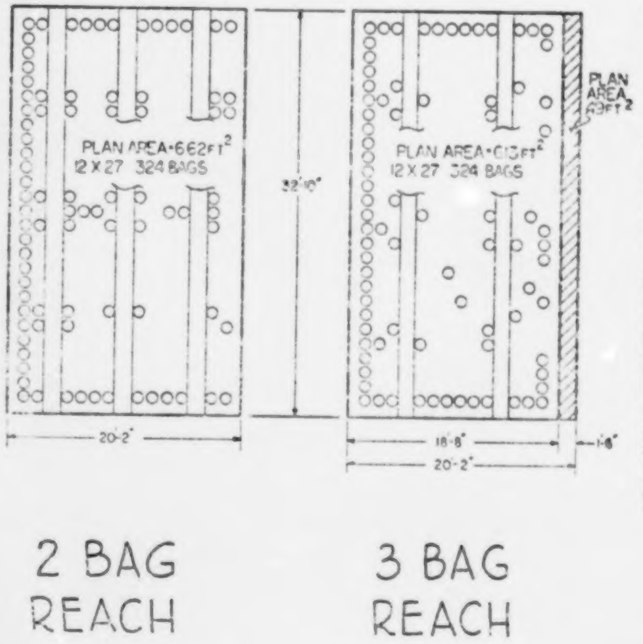
SLIDE NO. 9

STRUCTURAL BAGHOUSE FLY ASH COLLECTORS
UNITS 1-10
SHAWNEE STEAM PLANT
DESIGN CRITERIA

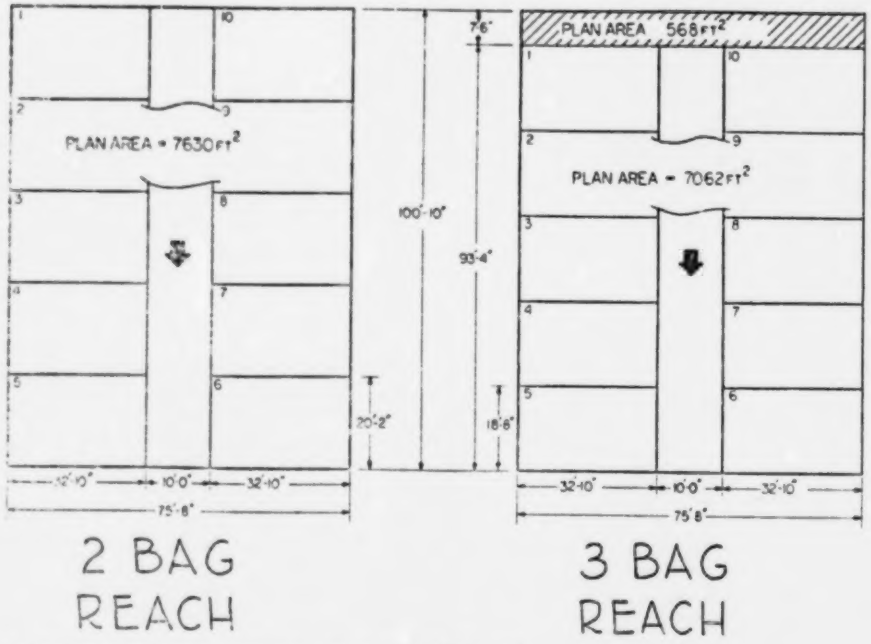
1. COAL - EITHER SEPARATELY OR BLENDED EASTERN OR WESTERN LOW-SULFUR COAL. SULFUR .33 PERCENT. MOISTURE 30.2 PERCENT. ASH 7.44 PERCENT. HEATING VALUE 8075 BTU/POUND.
2. ACFM - TEST BLOCK 650,000 WITH NORMAL OPERATION 585,000.
3. A/C - ALL COMPARTMENTS ONLINE AT TEST BLOCK 2.0 (THIS WILL BE EXPLORED LATER IN THE PAPER IN GREAT DETAIL).
4. BAG - 11-7/8" DIAMETER BY 34'-7-3/4" FIBERGLASS BAG COATED WITH TEFLON B FINISH; 9% BY WEIGHT.
5. CORTEN CASING, HOPPERS, DUCTWORK, AND ALL GAS CONTACT SURFACES.
6. STAINLESS STEEL BAG HARDWARE AND POPPET VALVE SHAFTS AND SEALS.
7. DRY FLY ASH HANDLING SYSTEM TO POND AND THEN WETTED.
8. FANS, DAMPERS, EXPANSION JOINTS, CONTROL HOUSES, AND RELATED EQUIPMENT NECESSARY FOR THE OPERATION OF THE BAGHOUSE.
9. EACH BAGHOUSE HAS 10 COMPARTMENTS WITH 324 BAGS PER COMPARTMENT. BAGS ARE ARRANGED ON 14-INCH CENTERS WITH TWO BAG REACH PROVIDING A GRID OF 12 BY 27 (3 WALKWAYS).

SLIDE NO. 10

STRUCTURAL BAGHOUSE FLY-ASH COLLECTORS
SHAWNEE STEAM PLANT UNITS 1-10
TWO VS. THREE BAG REACH
GRID ARRANGEMENT



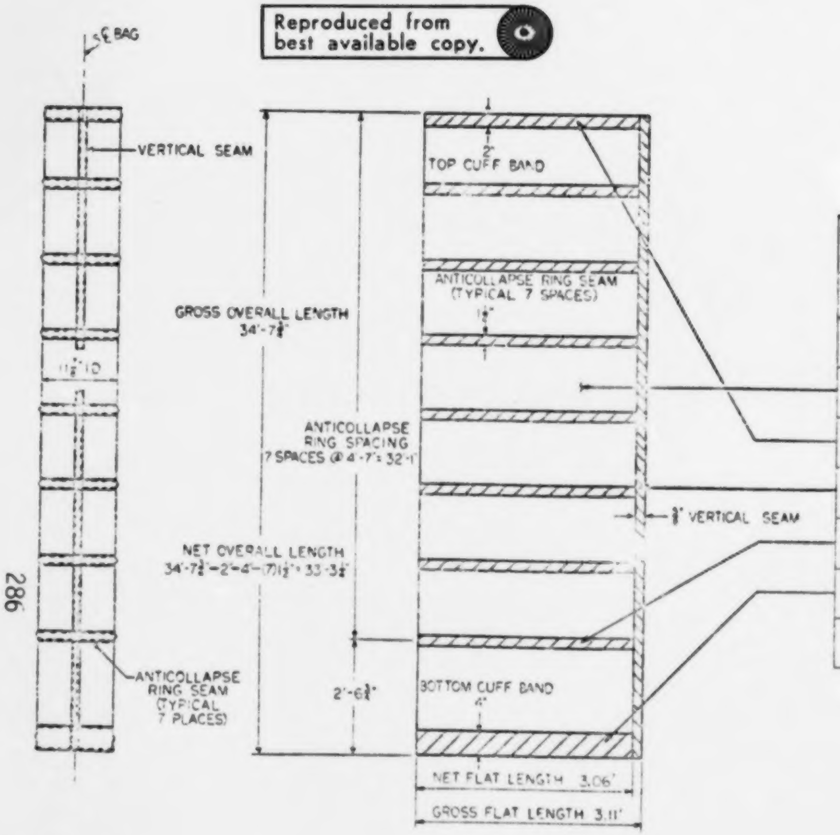
STRUCTURAL BAGHOUSE FLY-ASH COLLECTORS
SHAWNEE STEAM PLANT UNITS 1-10
TWO VS. THREE BAG REACH
BAGHOUSE ARRANGEMENT



RATIO OF PLAN AREA OF 3 BAG VS 2 BAG REACH = $\frac{7062}{7630}$ = 93%

SLIDE NO. 11

Reproduced from best available copy.


℄ BAG
VERTICAL SEAM
$11\frac{1}{2}$" I.D.
ANTICOLLAPSE RING SEAM (TYPICAL 7 PLACES)
GROSS OVERALL LENGTH 34'-7$\frac{3}{8}$"
ANTICOLLAPSE RING SPACING 7 SPACES @ 4'-7" = 32'-1"
NET OVERALL LENGTH 34'-7$\frac{3}{8}$"−2"−4"−(7)1$\frac{1}{2}$" = 33'-3$\frac{3}{8}$"
2'-6$\frac{3}{8}$"
2"
TOP CUFF BAND
ANTICOLLAPSE RING SEAM (TYPICAL 7 SPACES)
1$\frac{1}{2}$"
$\frac{3}{8}$" VERTICAL SEAM
BOTTOM CUFF BAND
4"
NET FLAT LENGTH 3.06'
GROSS FLAT LENGTH 3.11'

TYPICAL BAG CONFIGURATION

FLAT CLOTH LAYOUT

ACTIVE CLOTH AREA DETERMINATION

	LOCATION	SQ.FT.
1	OVERALL CLOTH AREA	107.71
2	TOP CUFF SEAM AREA	-.51
3	VERTICAL SEAM AREA	-1.80
4	ANTICOLLAPSE RING SEAM AREA	-1.91
5	BOTTOM CUFF SEAM AREA	-1.02
	TOTAL ACTIVE CLOTH AREA/BAG	102.47

CLOTH AREA SUMMARY

CLOTH AREA	BAG SIZE (SQ. FT.)		Δ CLOTH AREA (SQ. FT.)
PER BAG	107.71	102.47	5.24
PER COMPARTMENT (324 BAGS)	34,898	33,200	1698
PER COLLECTOR (10 COMPARTMENTS)	348,980	332,003	16,977

FABRIC FILTER
ACTIVE CLOTH AREA
STRUCTURAL BAGHOUSE
SHAWNEE STEAM PLANT
UNITS 1-10

SLIDE NO. 12

AIR TO CLOTH RATIO
BASED ON ACTIVE CLOTH AREA (102.47 SQUARE FEET/BAG)
STRUCTURAL BAGHOUSE - UNITS 1-10
SHAWNEE STEAM PLANT

	TEST BLOCK (EXCLUDING REVERSE AIR) 650,000 ACFM	TEST BLOCK (INCLUDING REVERSE AIR) 708,000 ACFM	NORMAL OPERATION (EXCLUDING REVERSE AIR) 585,000 ACFM	NORMAL OPERATION (INCLUDING REVERSE AIR) 643,000 ACFM
ALL COMPARTMENTS ON LINE (10)	1.96	*	1.76	*
ONE COMPARTMENT DOWN FOR CLEANING (9)	2.18	2.37	1.96	2.15
ONE COMPARTMENT DOWN FOR CLEANING AND ONE DOWN FOR MAINTENANCE (8)	2.45	2.67	2.20	2.42

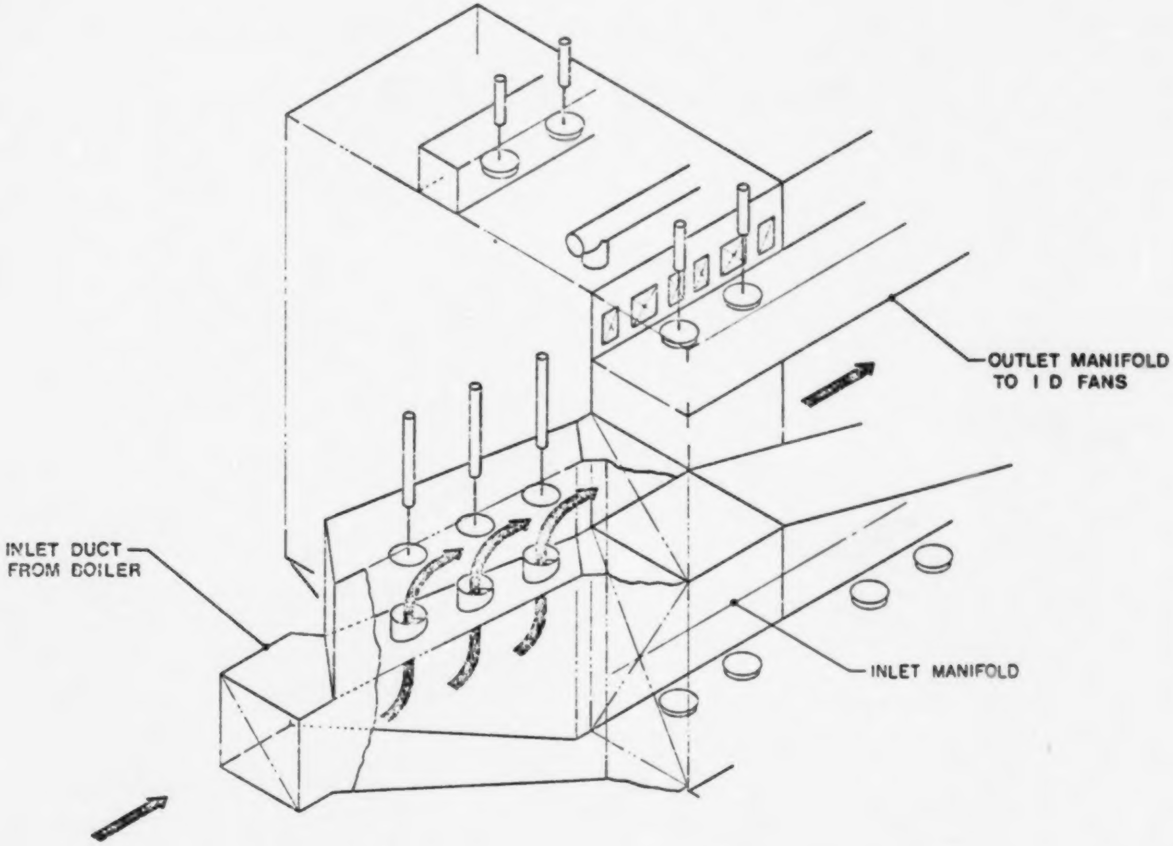
*REVERSE AIR IS NOT ON WHEN 10 COMPARTMENTS ARE FILTERING.

SLIDE NO. 13

STRUCTURAL BAGHOUSE FLY ASH COLLECTOR
SHAWNEE STEAM PLANT UNITS 1-10
PERFORMANCE AND GUARANTEE DATA
TVA AND ENVIROTECH

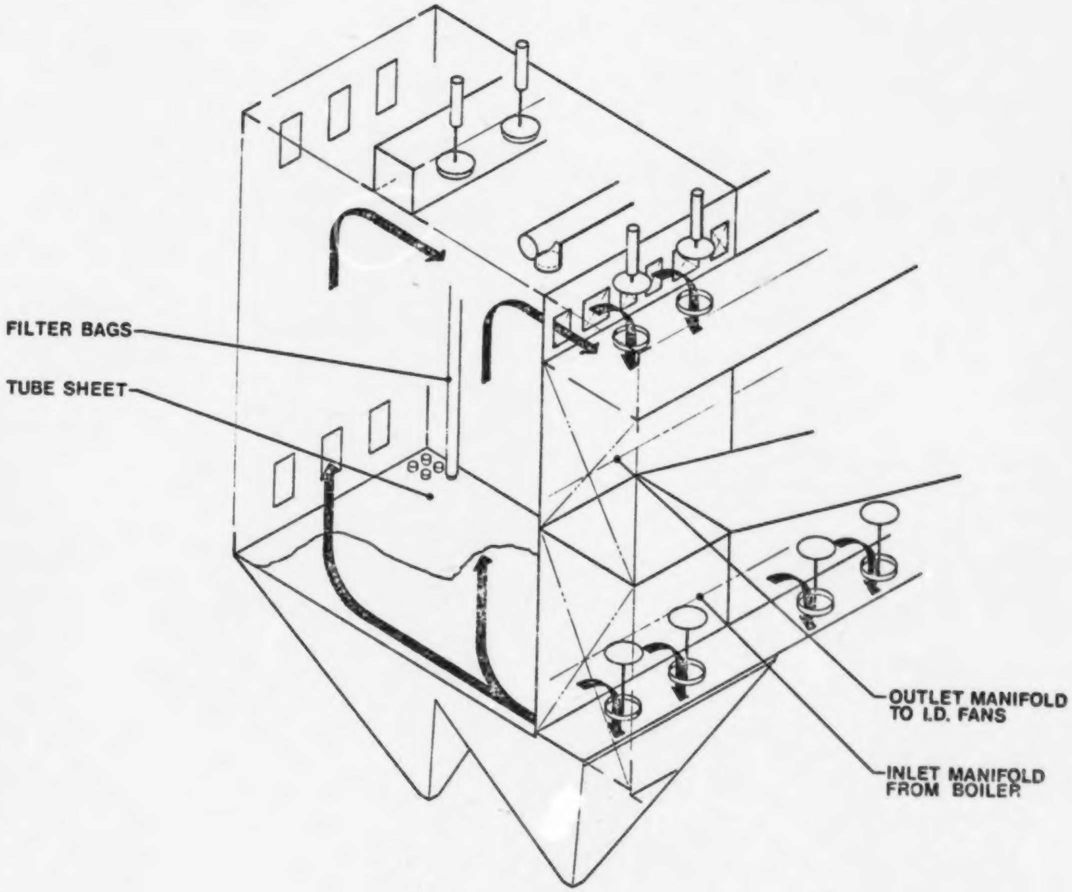
	SPECIFICATION REQUIREMENT	ENVIROTECH OFFERED
MAXIMUM ALLOWABLE OUTLET GRAIN LOADING (GRAIN/ACF)	.005	.005
MAXIMUM ALLOWABLE PRESSURE DROP (INCHES OF WATER)	6-3/4	5-7/8
FABRIC FILTER BAG LIFE (YEARS)	2	3

SLIDE NO. 14



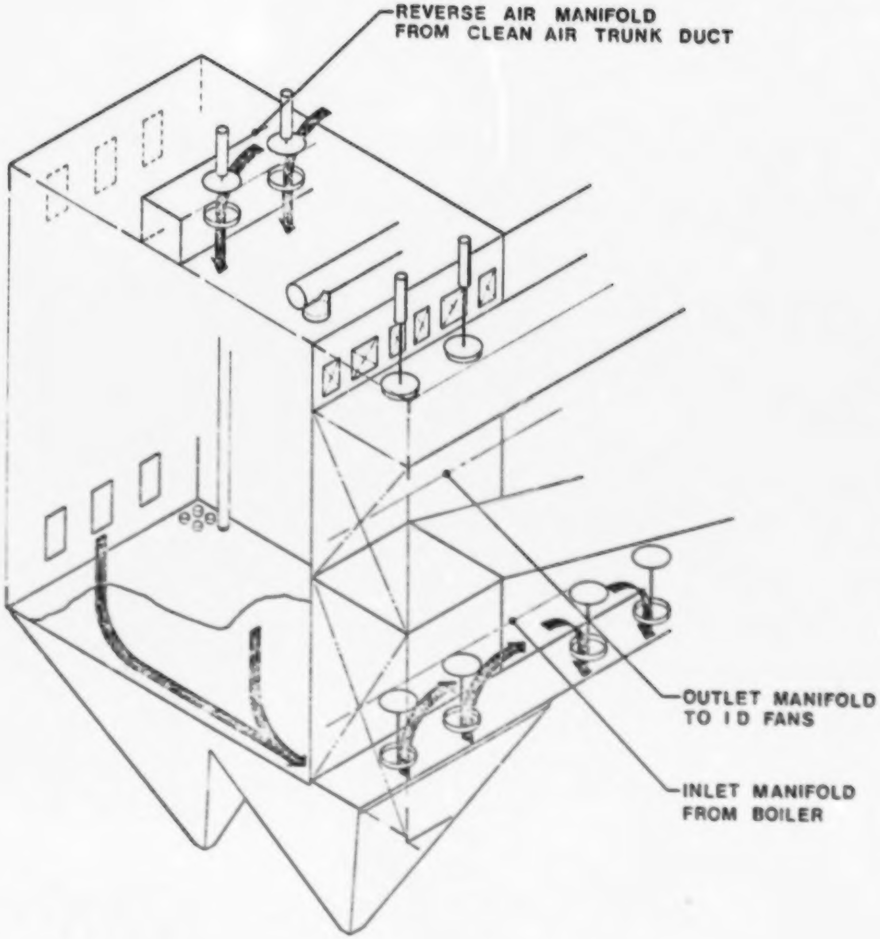
FILTER BYPASS

SLIDE NO. 15



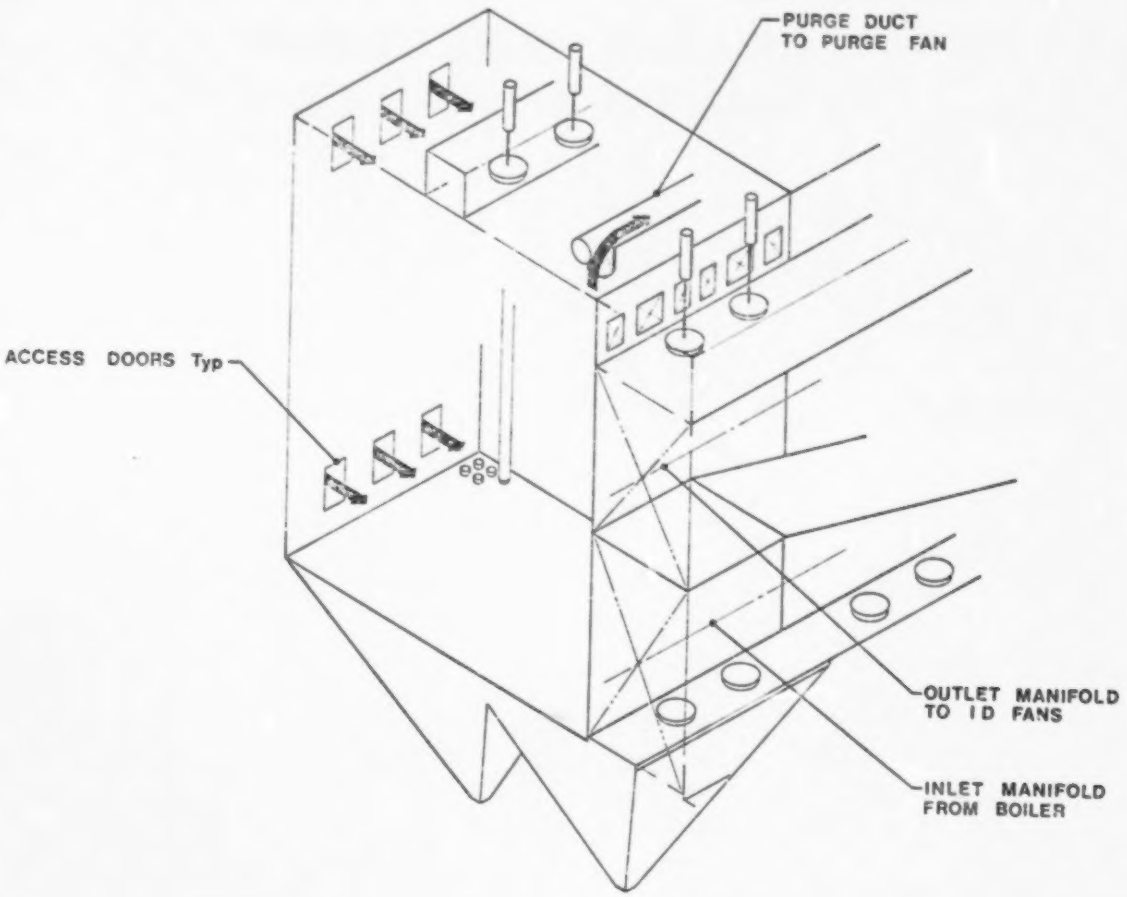
FLUE GAS FILTERING

SLIDE NO. 16



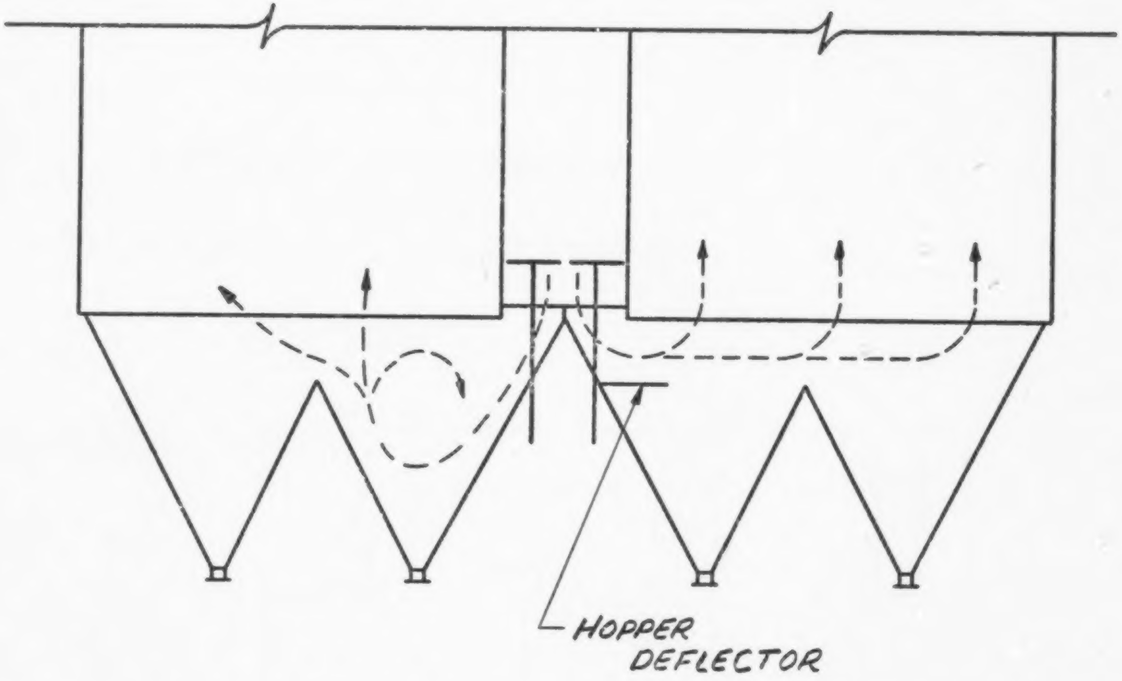
REVERSE AIR CLEANING/
COMPARTMENT WARMING

SLIDE NO. 17



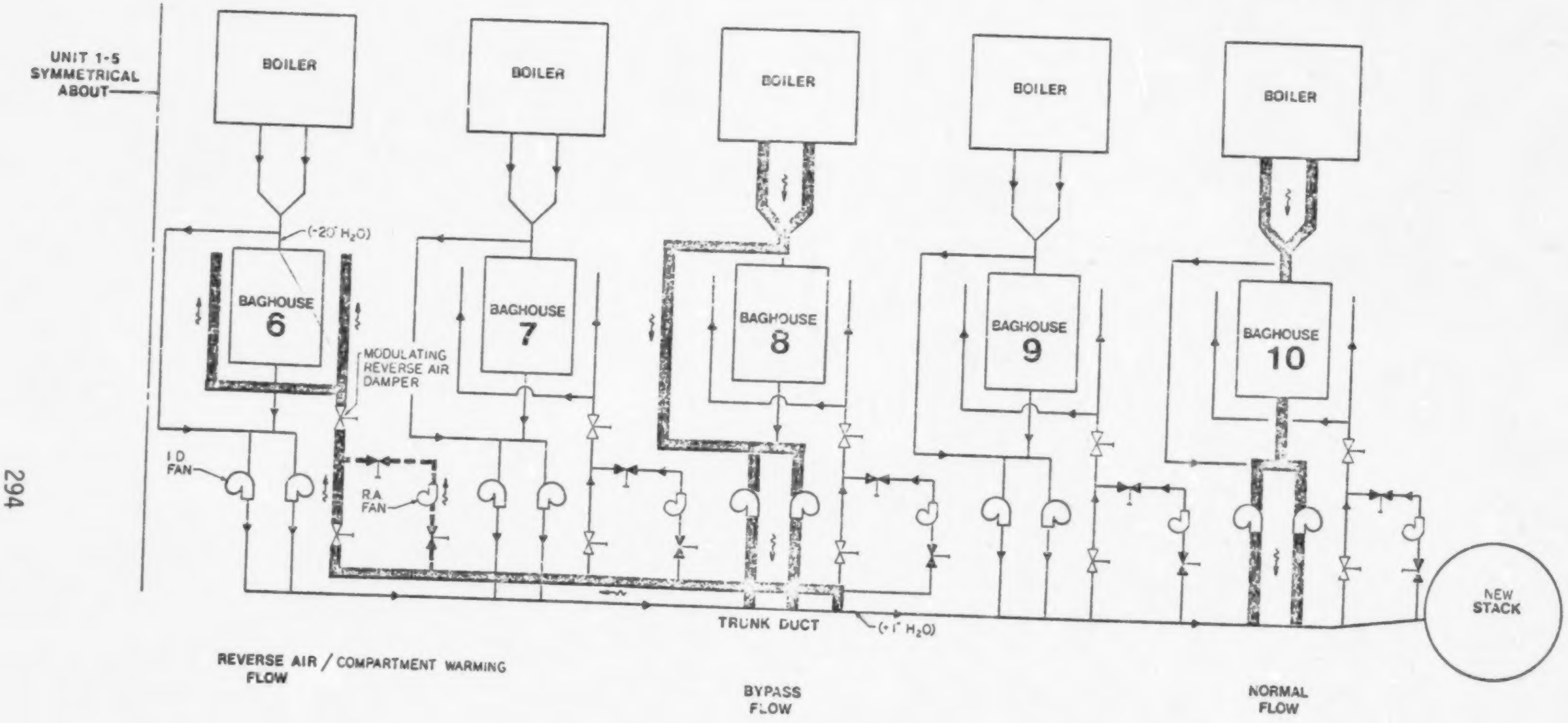
PURGE FOR MAINTENANCE

SLIDE NO. 18



HOPPER FLOW DEFLECTOR

SLIDE NO. 22



TVA SHAWNEE STEAM PLANT
UNITS 1-10
BAGHOUSE FLOW DIAGRAM

SLIDE NO. 23

FABRIC FILTER QUALITY ASSURANCE PROGRAM

I. BAG HARDWARE: INSPECTED AT 10% RANDOM SAMPLE, MINIMUM. INCLUDES WELD STRENGTH TESTS ON ANTI-COLLAPSE RINGS.

II. FABRIC: IN-HOUSE FIBERGLASS ROLLS ARE INSPECTED 100% FOR ROLL NUMBERS, LOT NUMBERS, AND TEST CERTIFICATIONS.

III. THREAD: TESTED FOR STRENGTH, PLIES AND COMPLIANCE TO SPECIFICATIONS.

IV. EQUIPMENT: MACHINES ARE INSPECTED FOR PROPER OPERATION AND FUNCTION, INCLUDING LAYOUT TABLE MARKS.

V. FABRICATION: WORKMANSHIP IS CHECKED AT ALL WORK STATIONS; LAYOUT, SEAMING, RINGING, CUFFING, PACKAGING. CLOTH CONDITION IS INSPECTED AT EACH WORK STATION.

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SLIDE NO. 24

FILTER CLOTH TEST CERTIFICATIONS

TEST	METHOD
WEIGHT	ASTM D1910
THICKNESS	ASTM D1777
COUNT *	ASTM D1910
PERMEABILITY	ASTM D737
TENSILE STRENGTH *	ASTM 1682 - METHOD IR-T
MULLEN BURST	ASTM D231
MIT FLEX	
ORGANIC CONTENT	ASTM D578
WATER REPELLANCY	ASTM D2721
YARN WEIGHT	ASTM D578
YARN TWIST *	ASTM D578
MICROSCOPIC EXAM *	

* WARP AND FILL

OPERATING CHARACTERISTICS OF A FABRIC FILTER ON A PEAKING/CYCLING BOILER WITHOUT AUXILIARY PREHEAT OR REHEAT

By:

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A fabric filter system has been on-line for one year on a coal-fired boiler that is primarily a peaking unit within the power schedule. For the first six months, Eastern Kentucky coal with 2.5 percent sulfur was the fuel source for 30 percent of the time, with low-sulfur Montana coal constituting the remaining fuel during the operation period.

Bag life has been excellent with no bag failures reported to date, and pressure drops have been low. There has never been an auxiliary heat source to preheat the fabric filter for start-up, nor to reheat the fabric filter when operating at reduced load with associated low back-end temperatures.

Conclusions are that the filter cake formed does protect the bags from blinding at low load conditions, and a special acid-resistant finish applied to the glass fibers protects the bags when high-sulfur coal is burned at low temperatures. Overall, this installation provides an excellent data base for cycling service and high-sulfur coal usage with a fabric filter.

OPERATING CHARACTERISTICS OF A FABRIC FILTER ON A PEAKING/CYCLING BOILER WITHOUT AUXILIARY PREHEAT OR REHEAT

THE HISTORY OF ELK RIVER POWER PLANT

In 1951, United Power Association began coal-fired electrical generation utilizing two stoker-fired units at the Elk River Station. In 1959, Unit 3 went on-line with a generating capacity of 25 MW. In 1964, this unit was one of the first turbine generators in the country to have steam supplied from a nuclear reactor. The nuclear program proved quite successful but was discontinued in 1968 and the reactor was dismantled in 1971 due to the lack of economics for such a small unit.

All three units have the capability to burn coal, oil, or natural gas. From mid-1975, the plant operated on oil or natural gas in order to meet State and Federal particulate emission limitations. With the impact of rising oil costs in the mid-1970's, the decision was made in 1976 to switch the plant back to coal-burning operation. In order to do this, it was necessary to satisfy the particulate emission limits of the state of Minnesota. After careful evaluation, a fabric filter was selected to be the control device. Since the station is not a base load plant, it is not feasible to secure long-term coal commitments. The stoker-fired units have test-burned refuse, wood chips, sawdust, and tire chips in combination with coal. Therefore, fuel variations can be quite broad, and the fabric filter's inherent ability to meet rigid air pollution standards on a wide variety of fuels was the determining factor.

In January, 1977, under a specification prepared by Black & Veatch consulting engineers of Kansas City, Missouri, a contract was awarded to Research-Cottrell to supply, fabricate, and erect the baghouse. Research-Cottrell's portion of the contract was completed in November, 1977, and the resultant general construction work was completed in May, 1978. On June 2, 1978, the baghouse facility began operation with the Elk River units burning coal.

GENERAL DESIGN APPROACH

Prior to 1978, the boilers dispersed flue gases into the atmosphere through three separate stacks; however, a decision was made to cap the three stacks with a by-pass damper in each stack and run flue work across the top of the power plant to the rear of the plant where the baghouse would be installed. Black & Veatch engineers analyzed the alternatives and determined that a substantial savings could be gained by installing one baghouse for the entire plant rather than three smaller units. This system has indeed been effective and has not caused any particular boiler problems. The fabric filter was installed and two half-capacity booster fans purchased to accommodate the additional pressure drop that would be created by the baghouse. A new metal stack was erected at the rear of the plant to disperse the clean flue gases into the atmosphere.

The primary fuel source of the plant is low-sulfur, Montana coal from Colstrip, Montana. However, a 20,000 ton stockpile of low-sulfur, Kentucky coal will be used as necessary when mine service or rail deliveries do not meet the requirements. Also, the plant is derated by approximately 10 MW when burning Montana coal. Kentucky coal will be burned when the extra generation needed justifies the premium cost of this coal. Approximately 10,000 tons of Montana coal are retained as inactive reserve.

A listing of the fuels which have been burned to date and the fuel characteristics are as follows:

1. Montana Coal

   Sulfur - 0.90 percent
   Moisture - 25.36 percent
   Ash - 9.17 percent
   Heating value - 8,447 BTU/lb.

2. Eastern Kentucky Coal

   Sulfur - 1 to 3 percent
   Moisture - 10 percent
   Ash - 10 percent
   Heating value - 12,500 BTU/lb.

3. Rubber Tire Chips

   A test burn of five percent and ten percent tire chips in combination with coal was conducted in June, 1979. A complete report will be made available from United Power Association or the Minnesota Pollution Control Agency. Preliminary results indicate no problems in burning tire chips in combination with coal in a stoker-fired unit. The ΔP across the baghouse increased slightly when burning tire chips, which indicates extra fly ash, or more likely, extra carbon particles from the tires. The test analysis of the ash will define any changes in carbon content or size distribution.

It was decided that reverse air cleaning with fiberglass bags would be utilized. The gas-to-cloth ratios, as presented in Table 1, might seem aggressive if this were a base-load plant. It is important to point out that the design volumes are at full load, and since the baghouse operates on a wide range of boiler loads, it was not required to be overly conservative in the design approach.

In reality, the average gas-to-cloth ratios in the gross and net mode are substantially less than the design numbers as presented.

The construction technique employed for the eight compartment unit is a modified modular method to increase work in the fabricating shop and decrease field labor hours. This system approach proved very economical and even allowed Research-Cottrell to do a portion of the final field assembly at grade when the support steel construction was behind schedule. The added benefit of this approach on this size unit is the additional quality control that is gained by greater shop fabrication.

The fiberglass bags were supplied by Globe-Albany Filtration and are their Q78 design. A breakdown of the bag characteristics are as follows:

Type: Fiberglass with acid-resistant finish.

Specification:
Weight - 14 oz./yd.^{2}
Permeability - 35-50
Count - 44 x 24
Weave - 3 x 1 twill
Size - 8" diameter x 264" long

Components supplied with each bag:

Research-Cottrell snap ring to facilitate installation/replacement.

Banded top with disposable cap.

Four anti-collapse rings.

Advantages:
Resistant to acid attack.
Encapsulated fibers.
Superior lubricity for flexing ability.

The precoating of the bags was accomplished by bringing all three units to full power with the by-pass dampers open and the flue gases dispersed directly into the atmosphere. The baghouse damper was opened and one module of the baghouse was then slowly placed on-line. As each module was coated with fly ash, another module inlet damper was opened. After all modules were coated, the by-pass dampers were closed and the flue gases entered the baghouse.

Subsequent plant operation has required that the pulverized coal unit be started on oil and then switched to coal. Initially, the by-pass dampers were opened when operating on oil; however, this created an emission of black smoke. Therefore, it is necessary to utilize the baghouse 100 percent of the time. In this case, the oil smoke passes through the filter bags, which have been cleaned subsequent to the previous shut-down. There has been no indication of blinding of the bags.

EXPERIENCE TO DATE

Baghouse operation has been extremely satisfactory and reliable to date. Bag failures have been non-existant. The on-line reliability has been excellent with no unscheduled outages of the boiler load due to problems with the fabric filter. Since the plant is subject to frequent cycling and peaking demand loads, the number of cold starts in the past 13 months has been extensive. Pressure drop across the unit has been within the design parameters; Figure 1 indicates the drop across the cloth at various boiler loads. When operating at full design load, the gas volumes have even exceeded the original design volume and the baghouse is in the constant cleaning mode. The pressure drop on the flange-to-flange unit in no case exceeds 8". A Dynatrol opacity monitor is installed in the stack for a continuous readout. The opacity since start-up has been essentially zero. During warm weather it is extremely difficult to ascertain whether the plant is even on the line. In colder weather there is a slight vapor plume but it dissipates quite readily and has no visible trail. This has turned out to be an advantage that we didn't anticipate and affords good community relations between United Power Association and the local population.

Baghouse performance tests were conducted on July 25, 1978, and the results are shown in Table 2. Since these tests were conducted very close to the start-up of the unit, and during the weeks preceeding the tests the unit had not been on-line, we would expect better results today with a more adequate filter cake on the bag surface.

During the test, problems were encountered which resulted in increased air volume across the baghouse. We could only attribute this to leakage around the module doors, and subsequent discovery of corrosion on the inside of the door seals proved this to be correct. We feel the problem has now been corrected. There were also minor problems with the seals on the poppet damper operators located on top of the baghouse. This has also been corrected and is not recurring.

Located just inside the boiler housing adjacent to the baghouse site is a dryer for the compressed air supply. This proved quite reliable during the very cold winter months and no freezing problems of compressed air were experienced in the pneumatic operators supplied. The piping to the pneumatic operators is not insulated.

Subsequent tests have also indicated incomplete combustion of the stoker-fired units and a rather high carbon carryover to the baghouse. To date this has not caused any noticeable problems either due to high pressure drop across the fabric or fires in the baghouse hoppers. The ash is pulled every eight hours during full load operation. A breakdown of the ash analysis from the stoker and pulverized coal units is shown in Table 3 for your review.

FABRIC CONSIDERATIONS AND FABRIC TESTING PROGRAM

Experience with fabric collectors on both industrial and utility coal-fired units had not been conclusive as to the need for auxiliary preheat. The specification and fuel variations contained sulfur as low as 0.3 percent and as high as 2.0 percent.

Figure 2 depicts a preheat system utilizing steam coils and the reverse air fan system to raise the temperature from ambient to at least 250°-300°F. The cost per year, based upon a 30% load factor,would be $11,880 per year for 200 cold starts.

More costly would be a separate reheat system to raise the temperature at low load conditions from 190°-220°F. to 250°-300°F. This system as shown in the figure could cost $27,878 per year.

Therefore, the operating cost for both the preheat and reheat would be $.83/KW. These figures reflect only the cost for the necessary steam consumption, and do not include additional maintenance or capital costs.

The ability to operate the system without any auxiliary heat source offers a substantial savings to us, and simplifies the operation of the unit.

Research-Cottrell, upon addressing the fuel specification, proposed and recommended the acid-resistant finish as developed by Burlington Industries.

Tables 4 and 5 reflect the merits of this finish, as well as the justification of utilizing 14 oz. fabrics instead of 9 or 10 oz. The following steps explain the tests for the acid cycle:

A. Heat age fabric for specified time at 500°F.
B. Soak fabric in 5.0% Sulfuric Acid at 175°F. for 5 minutes.
C. Place samples (dripping wet) in oven at 450°F. for 5 minutes.
D. Repeat "B" and "C" for a total of 4 cycles.
E. Heat for one hour at 500°F. in oven.

The results to date are extremely encouraging. Figure 1 depicts the severity of the operation when partially burning 2 percent sulfur Eastern Kentucky coal. Particularly note that the system operates at a temperature as low as 190°F. to 220°F. for sustained periods of time.

Since the bags have the potential for requiring high maintenance, we were concerned about bag life and the ability to operate the baghouse on such cycling/peaking service. The plant averages about four (4) cold starts a week for two (2) months in the summer and four (4) months in the winter. Therefore, in a year's time the bags have been through the dew point at least 200 times. Upon the recommendation of Research-Cottrell, the hopper heaters were left on during all shutdowns. After two or three months of operation, United Power Association approached Research-Cottrell and questioned the necessity for continuous operation of the hopper heaters. Inasmuch as the bag testing program is ongoing, we agreed to observe the results monthly for undue degradation. Since October 1978, the heaters have been left on only during low load conditions and shut down after the plant is taken off the line and baghouse flyash pulled. No detrimental effects have been observed to date. The load of the hopper heaters is 112 KW.

For the bag testing program, every few months a bag is removed and sent to a testing laboratory. The major areas to review are as follows:

Mullen burst

The pressure necessary to rupture a secured fabric specimen - #/in.^{2}.

Permeability

The ability of gas to pass through the fabric, expressed in cubic feet of gas per minute per square foot of fabric with an 0.5" H_2O pressure differential.

Count

The number of warp yarns and filling yarns per inch.

Tensile strength

The ability of yarns or fabric to resist breaking by direct tension. Ultimate breaking strength is expressed in pounds per inch. (Increase in fabric weight means increased strength due to greater bulk density which can be expected to yield longer service life.)

Loss of ignition (L.O.I.)

Heat cleaning the fabric to remove the finish, starches, collected particles, etc., and comparing initial weight to final weight.

MIT (fold flex endurance test)

Using a Tinius Olsen Folding Endurance Tester, internal abrasion is tested by folding a sample through 270°, 180 times per minute. The samples are 5 inches long and 1/2" wide with a four-pound weight attached to one end. Tests are performed at room temperature.

A summary of the test report is shown in Table 6.

There has been no significant decrease in the mullen burst strength. It is important to note that the permeability after 12 months is unchanged. This verifies that the interstices of the weave have not blinded due to condensation or acid attack. The tensile strength degradation levels out as expected. (See Figure 4)

Loss of ignition measurements indicate that the finish is stable. Since the acid-resistant finish is applied at a minimum of 4% by weight of the greige goods, the results clearly indicate its stability.

Probably the most important measurement is flex-to-failure tests that indicate individual fiber breakdown and fiber-to-fiber abrasion.

Figures 5 and 6 present curves which clearly show that the flex cycles have leveled out after one year of service, and bag life should exceed the two (2) years as predicted by Research-Cottrell and Globe-Albany.

SUMMARY

After one year of operation, the fabric collector has met and exceeded design expectations for the Elk River Station. The ability to bring the boiler on-line, operate at the low load, and shut down completely on a random schedule is a necessity of this plant within our power grid. The baghouse's response and reliability for this type of service has been proven, and certainly gives us confidence to consider the fabric filter for future requirements. The acid-resistant bags have alleviated our greatest fear--could the fabric withstand such vigorous service? For fuel variations with less than 2% sulfur content, we can speak with confidence that a fabric filter can be applied without the need or costly maintenance of a preheat system or a reheat system.

Table 1. BOILER AND FABRIC FILTER DESIGN DATA

Boiler Data

Unit #	Steam Rating	Type	Manufacturer
1	135,000 lb./hr.	Stoker	Springfield
2	135,000 lb./hr.	Stoker	Springfield
3	235,000 lb./hr.	Pulverized Coal	Riley

Fabric Filter Design Data

Flue gas volume	255,800 acfm @ 330°F
Inlet dust loading	1.0 to 1.5 grains/ACF
Gas-to-cloth ratio	2.15:1 Gross 2.45:1 Net
Number of bags per compartment	324
Number of compartments	8
Cloth area per compartment	14,904 sq.ft. (actual)
Bag size	8" diameter x 22' long

Table 2. PERFORMANCE TEST RESULTS, JULY 25, 1978, BAGHOUSE EMISSION RATE AND EFFICIENCY

Inlet

	Temperature in °F	Flow Rate in ACFM	Particulate Concentration in grains/ACF	Particulate Emissions in #/MM BTU
Test 1	330	262,027	0.9833	4.125
Test 2	-	-	-	-
Test 3	-	-	-	-

Outlet

	Temp. in °F.	Flow Rate in ACFM	Particulate Concentration in grains/ACF	Particulate Emissions in #/MM BTU	Percent Efficiency
Test 1	300	274,019	0.0039	0.017	99.59
Test 2*	293	265,038	0.0094	0.040	99.03
Test 3	290	268,457	0.0038	0.017	99.56

*The probe wash contained numerous particles larger in size than one would expect downstream of a baghouse. Probable cause — particles collected from the surface of the sampling port or were reintrained from the duct walls.

Table 3. MONTANA COAL - UPA/ELK RIVER STATION

Ash Analysis of February 16, 1979

(at air heater settling hoppers)

1. Unit 2, Stoker-fired

Sample	1	2	3	Average
Sulfur, %	0.95	0.88	1.02	0.95
Carbon, %	57.33	45.33	50.24	50.97

2. Unit 3, Pulverized coal-fired

Sample	1	2	3	Average
Sulfur, %	0.49	0.47	0.52	0.49
Carbon, %	-	-	-	-

Table 4. COMPARISON OF 9 OZ. VERSUS 14 OZ. GLASS FABRICS

	9 oz. Acid Resistant Finish	14 oz. Acid Resistant Finish
	Warp Filling	Warp Filling
Tensile Strength		
Original	325 x 185	668 x 360
MIT Flex		
Original	20,310 x 5,890	30,598 x 18,846
MIT Flex-Acid Cycle		
Original	20,310 x 5,890	30,598 x 18,846
4 hours @ 500°F	8,012 x 2,456	10,428 x 3,072
Mullen Burst	500	625
Yarn	150½ x 75½	37-1/10 x 75-1/3

Table 5. FINISHES TESTED AT VARIOUS TEMPERATURE LEVELS (FILLING YARNS ONLY)

	325°F		425°F		500°F	
Test	Acid Resistant	Teflon B @ 10%	Acid Resistant	Teflon B @ 10%	Acid Resistant	Teflon B @ 10%
Tensile						
Original	360	267	360	267	360	267
7 days	331	281	292	253	267	121
21 days	331	263	223	161	201	109
MIT Flex						
Original	18,846	9,826	18,846	9,826	18,846	9,826
7 days	10,600	7,200	6,000	3,700	6,546	625
21 days	10,600	3,200	7,600	1,300	4,346	114
MIT Flex Acid Cycle						
Original	18,846	9,826	18,846	9,826	18,846	9,826
4 hours	5,500	6	5,600	1	3,072	1
7 days	7,700	9	6,200	1	2,243	1
21 days	4,600	9	1,200	2	1,114	1

Table 6. UPA TEST REPORT

	New	Sept., 1978	Jan., 1979	May, 1979
Weight	13.5 ± .7			
Top*		20.3	16.9	19.6
Center*		21.6	18.6	18.8
Bottom*		19.7	18.1	21.2
Permeability	40-55			
Top		46.0	50.75	51.0
Center		42.0	60.25	55.0
Bottom		44.5	62.25	56.5
Strength (Warp/Fill)	668/360			
Top		558/283	433/235	480/195
Center		562/272	432/213	465/205
Bottom		581/281	423/240	455/213
Mullen Burst	540-600			
Top		525	645	520
Center		538	620	520
Bottom		518	605	580
M.I.T. (Warp/Fill)	30,598/18,846			
Top			2502/1106	3593/1099
Center		4500/1700	3517/880	3161/1367
Bottom			2779/898	3543/996
pH				
Top/Bottom	7 - 7½	4.3	-	-
LOI	4% minimum			
Top		3.7	4.5	4.8
Center		4.0	4.8	4.6
Bottom		3.8	4.7	4.6

*As reviewed

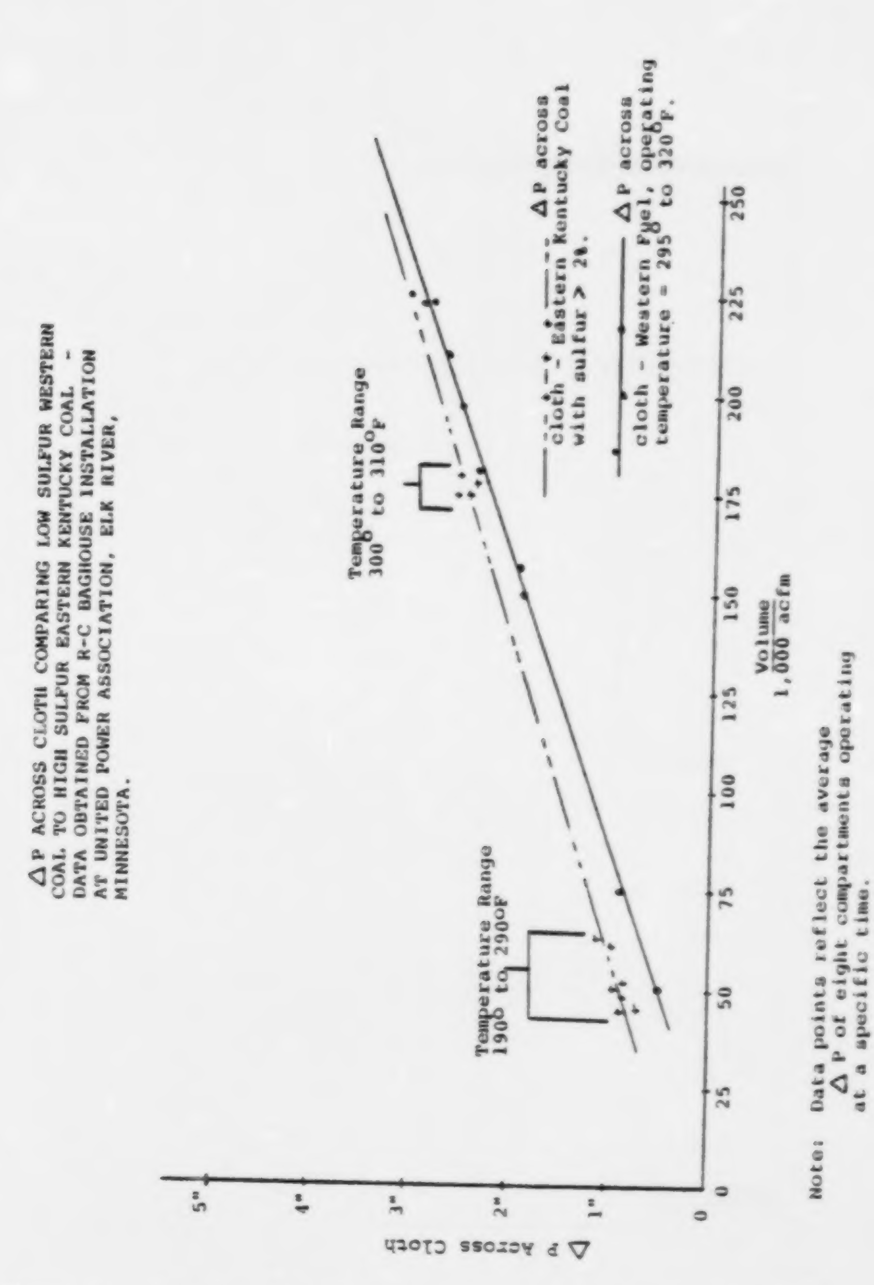

Figure 1. Pressure drop across the cloth at various boiler loads.

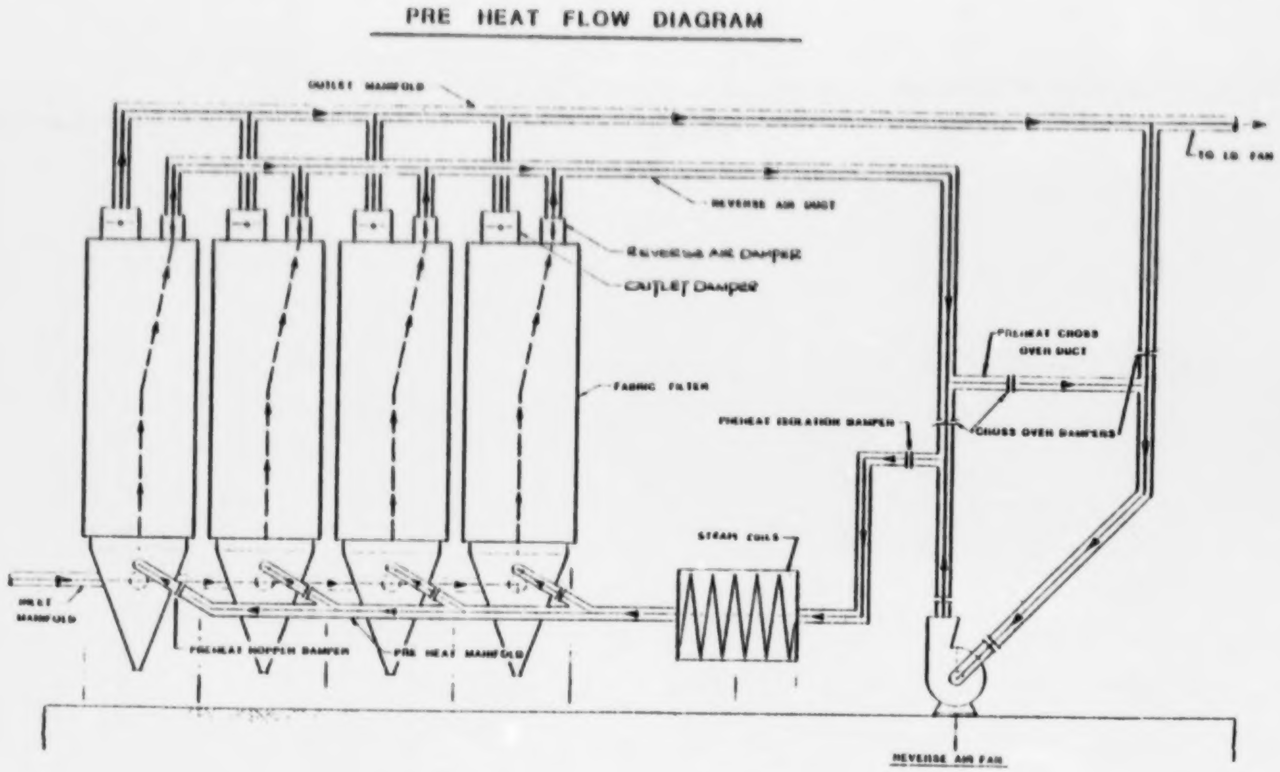

Figure 2. Preheat system.

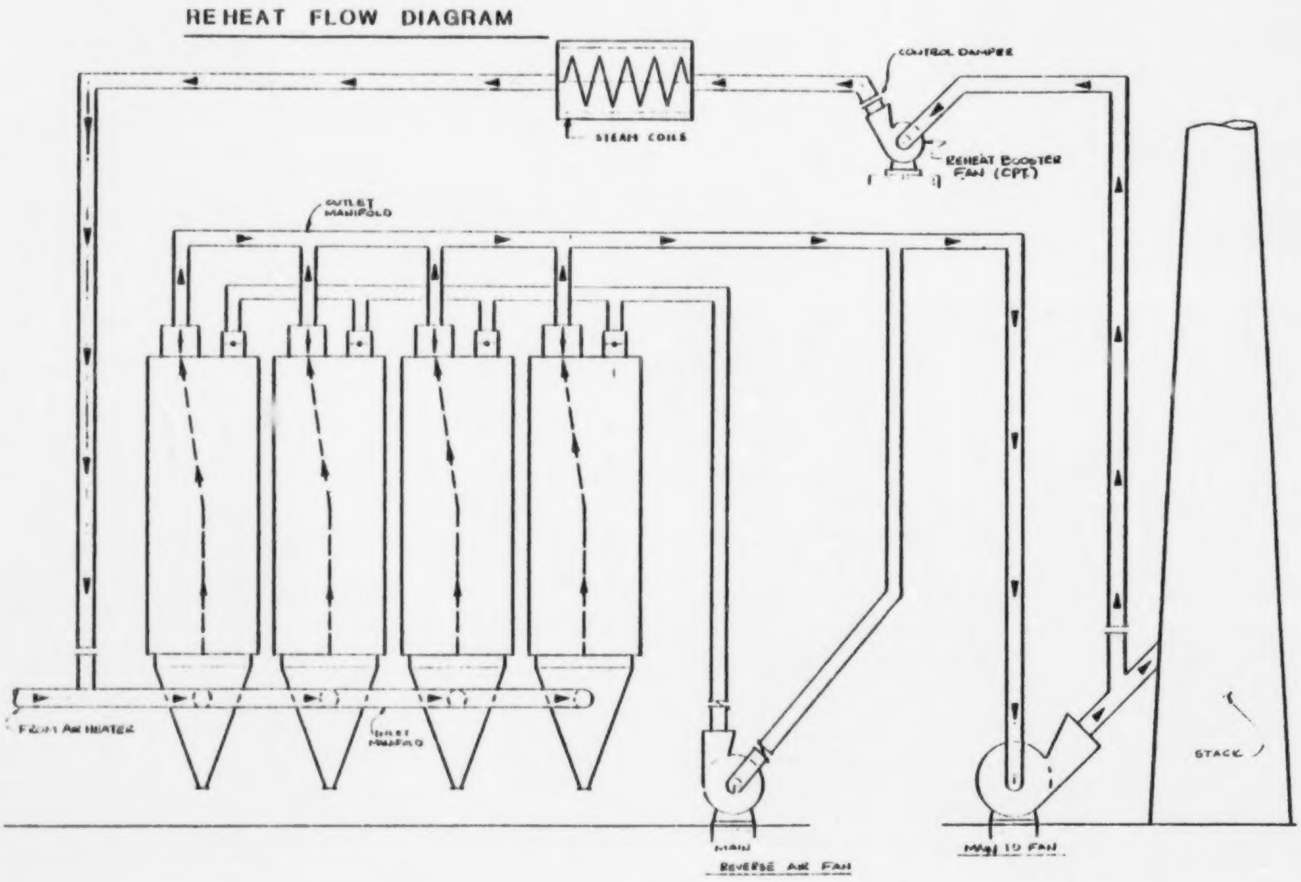

Figure 3. Reheat system.

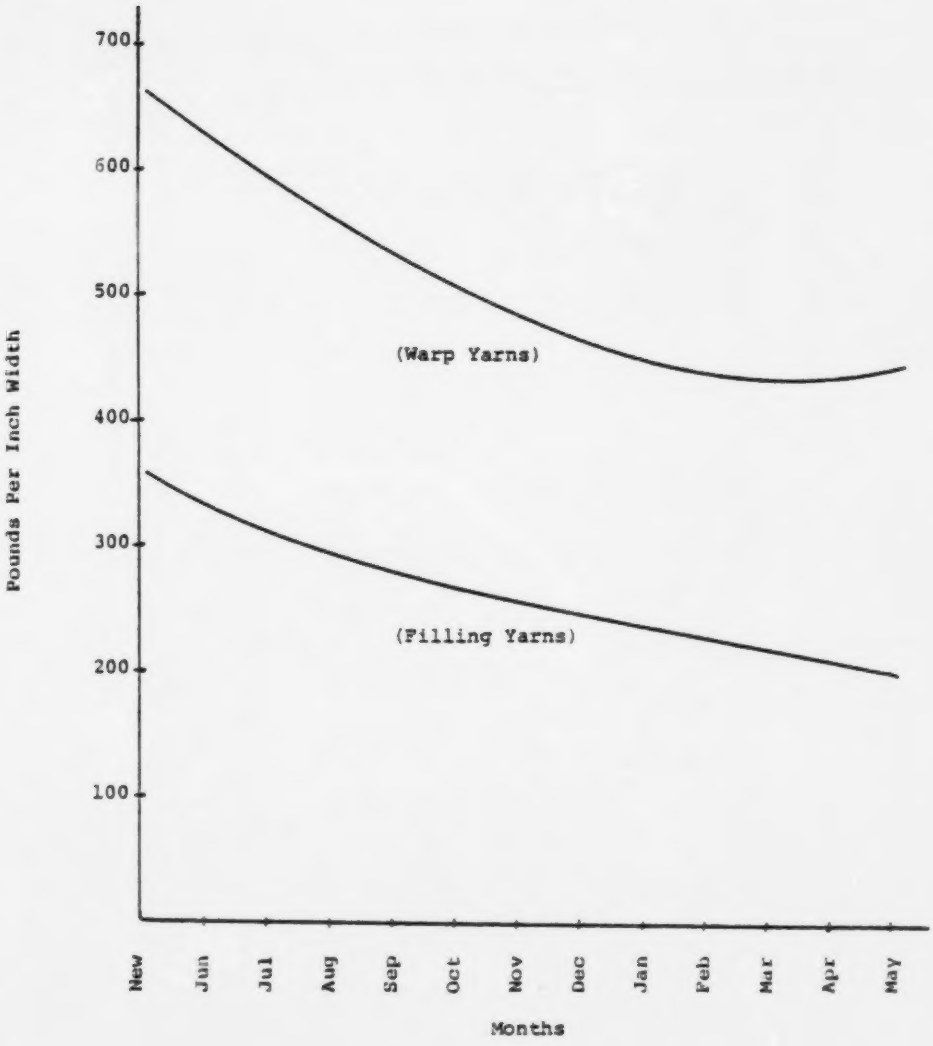

Figure 4. Tensile strength.

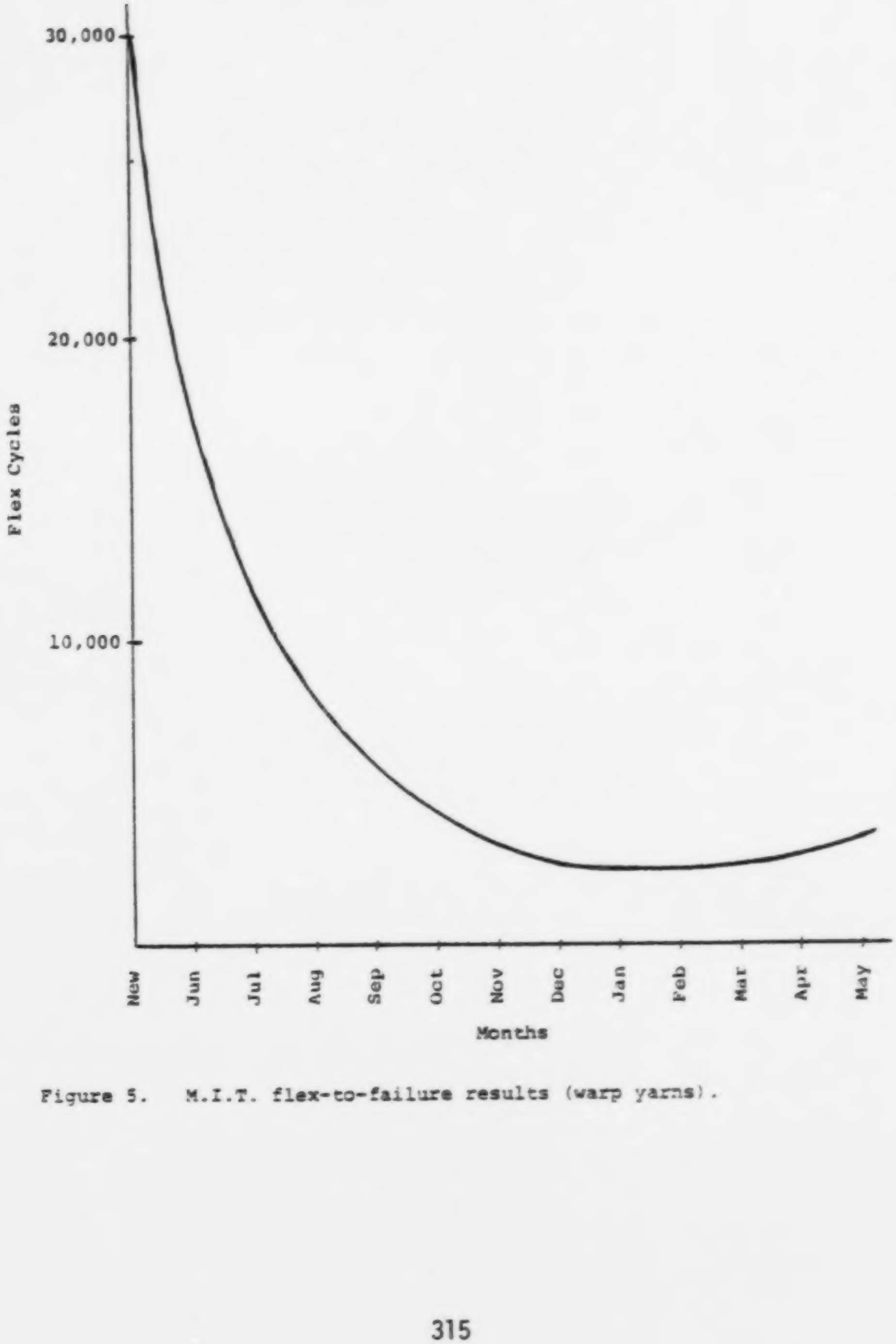

Figure 5. M.I.T. flex-to-failure results (warp yarns).

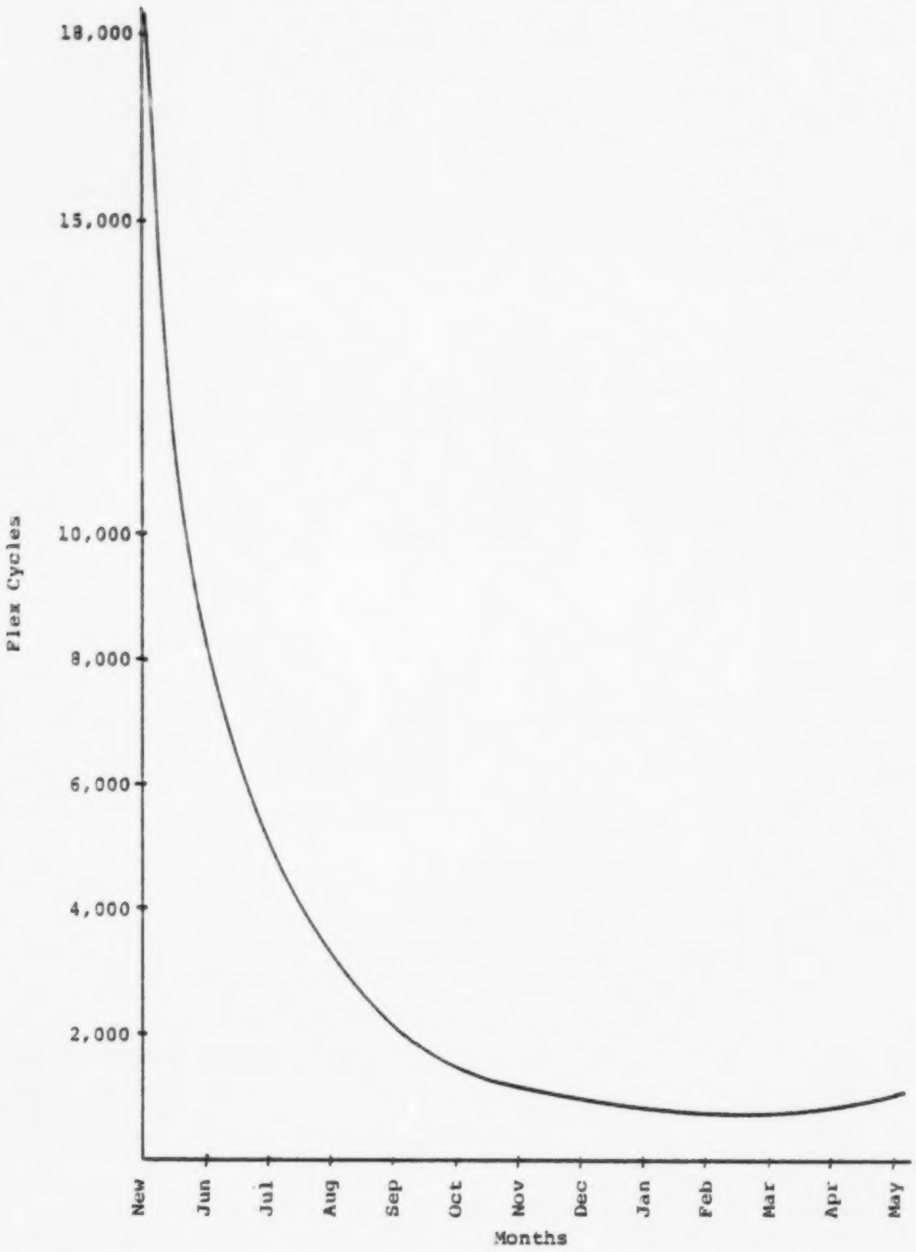

Figure 6. M.I.T. flex-to-failure results (filling yarns).

OBJECTIVES AND STATUS
OF
FABRIC FILTER PERFORMANCE STUDY

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ABSTRACT

In October 1977, Southwestern Public Service Company executed a contract with the U. S. Environmental Protection Agency that called for a study to assess the performance of a fabric filter system installed on a large utility boiler that utilizes low sulfur Western coal. The project is now into its second year and the objectives of this paper are to describe the scope and intent of the study, as well as to report progress to date. In addition, some of the difficulties that we have encountered are discussed. Although some of these problems have resulted in procedural changes, the intent of the study has not been altered.

This paper describes work being done in specific areas that both the EPA and Southwestern are connected with. These include fabric assessment, data collection, selection and installation of instrumentation, and overall fabric filter system performance. Results of the first performance test are also reviewed and the installation of a pilot baghouse is discussed.

This study is being performed under EPA Contract 68-02-2659.

OBJECTIVES AND STATUS
OF
FABRIC FILTER PERFORMANCE STUDY

I. INTRODUCTION

Southwestern Public Service Company is an electric utility headquartered in Amarillo, Texas. The Company has a generating capacity of 2,921,000 kW and supplies customers in a service area that stretches from the southwest corner of Kansas through the Oklahoma Panhandle, Texas Panhandle, South Plains of Texas, and the Pecos Valley region of Eastern New Mexico.

Southwestern Public Service Company is unique as a utility because it does all architectural and engineering design of its power plants. Throughout the planning, engineering, and construction of a generating facility, the structural, electrical, mechanical, and control engineering groups of the Plant Design Department interact to design efficient power plants. The design and construction of all Southwestern's transmission and distribution facilities is also the responsibility of in-house engineers.

Background

Harrington Station, Southwestern Public Service Company's (Southwestern) first coal-fired plant, went into operation in July 1976, with one 350 MW unit on line. Plans for the conversion to coal as a primary boiler fuel were begun in 1970 when Southwestern's management realized that future natural gas supplies could be affected by increasing prices, limited availability, and impending regulations. The search for alternative fuel focused on low sulfur Western coal. By 1971 the decision to convert to coal as a fuel base had been made and construction of Harrington Station began in 1974.

Harrington Station is located approximately 3.1 km (5 miles) northeast of Amarillo, Texas. A second 350 MW unit went on line in 1978, and Unit 3 is scheduled for completion in 1980.

The basic problem in designing Harrington's second coal-fired unit was the selection of a particulate emission control system which would satisfy the Environmental Protection Agency's (EPA) New Source Performance Standards (NSPS). Southwestern studied the existing alternatives for controlling coal-fired boiler emissions which would not require scrubbing for particulate removal. After comparing all parameters (design, operating, maintenance, costs) Southwestern wrote a set of specifications and then negotiated a contract for a fabric filter system (FFS) to be supplied by Wheelabrator-Frye, Inc. (WFI).

Objective of Study

Only a small amount of information on the performance of fabric filters at other utility installations was available when Southwestern was making its evaluation; therefore, when the EPA indicated its need for utility input on a comprehensive study of FFS, Southwestern agreed to participate, hoping other utilities might some day utilize the data to be collected. When the 2-year study has been completed, the following objectives will have been met:

1. full characterization of the fabric filter system applied at Harrington Station, Unit 2;
2. assessment of the technical and economic feasibility of the system;
3. determination of the system's optimum operating condition.

Following the testing phase of the program, operation and maintenance data will continue to be recorded until 1982 to determine the long-term reliability of the system. Special tests will be conducted through the use of an on-site pilot baghouse.

II. FIRST YEAR EXPERIENCE

Installation of Support System

Prior to start-up of the FFS it was necessary to install certain support systems for the collection of reliable data. The following systems were installed.

1. Instrumentation. Instrumentation was located so that the best possible monitoring of the gases entering and leaving the east and west baghouses could be used to evaluate the performance of these baghouses. Continuous monitors were placed on the stack so that trends could be established by composite sampling of flue gas conditions coming from both baghouses. It is to be understood that the location of the continuous monitoring devices is far from ideal, because of the short runs of flue gas duct prior to turns and transitions. The monitoring devices were located so that the best samples could be obtained without impeding access to the monitoring equipment.

Specifications for monitoring equipment needed to meet the study's requirements were submitted to bidders in October 1977. A review and evaluation of bids was completed in November 1977 and Lear Siegler and IKOR were the two major vendors selected. The following equipment was purchased:

5	Lear Siegler SM800, SO_2/NO Monitors,
5	Lear Siegler CM50, Oxygen Analyzer Control Monitors,
1	Lear Siegler Opacity Monitor,
4	IKOR Continuous Particulate Monitors,
2	Ellison Instruments Annubar,
20	Leeds & Northrup Recorders.

In addition, miscellaneous support equipment, thermocouples, and flow transmitters were purchased and a software program was developed.

Delivery of the equipment began in February 1978 and continued through April. Mounting, piping, and wiring of the instruments took place in May and

June; during July and August 1978, the Lear Siegler monitors were checked out, started up, and calibrated.

By September 1978 the Lear Siegler equipment was functional and most of the initial installation problems had been resolved. The equipment (with the exception of the IKOR particulate monitors) seems to be performing in an acceptable manner. With proper maintenance the Lear Siegler equipment is expected to continue to perform with a reasonable degree of reliability and accuracy. Calibration factors for the IKOR particulate monitors continue to be erratic. At this time it appears the IKOR particulate instruments may not produce any meaningful, quantitative data, although they will be left in place for the purpose of locating bag failures.

A record of each problem is maintained at the plant which indicates the date and time it occurred, how it was resolved, and when an instrument went back into service. Strip charts are also filed at the plant after they have been changed.

2. Datalogging System. One of the objectives of the FFS is to correlate manual sampling results with operating data to define the performance of the FFS; therefore, the parameters listed below are being continuously monitored at five points in the flue gas stream: SO_2, NO_x, O_2, particulate, flue gas flow, temperature, and duct pressure. Additional operating parameters being measured or calculated on a continuous basis are pressure drop across the system, power consumption, load on the unit, fuel flow, cleaning mode and cleaning frequency. This data will not be as specialized as the manual sampling information; its purpose is to represent everyday operation of the FFS.

The FFS programs are executed under the sublevel processor of the Unit 2 computer. The plant computer is a Westinghouse Model W2500, 16 bit, real time computer with a one million word disc, and 64 k words of core. All contact and analog inputs from the five sampling stations are recorded by the computer, which also has access to other performance parameters concerning the plant.

3. EPA Trailer. In order to accommodate the extra equipment and personnel required for special testing, it was felt a mobile laboratory facility should be made available for use during the testing phase of the project. The EPA had a 9.1 m (30-foot) trailer available for the project work and upon completion of the necessary paper work the trailer was delivered to Harrington Station on May 12, 1978.

After necessary repairs had been made, the mobile lab was parked underneath the FFS, north of the control room. This position offers natural protection from the elements and is also easily accessible from the different sample locations. The trailer will remain at this location for the duration of the project.

4. Manual Stack Sampling Equipment and Sampling Sites. A part of the study is to perform manual sampling of the flue gas materials entering and leaving the east and west baghouses as well as the composite of the gases leaving the stack.

To accomplish this manual flue gas sampling, ports were designed and installed in the inlet and outlet of each baghouse. These four sampling points do not meet the ideal characteristics of static flow for sampling in a duct. The sampling platform which is on the stack does meet the criteria of stable flow and also has provided the most consistent results.

As indicated in this paper, efforts to confirm the actual volume of gas flow through the baghouses, by performing pitot tube traverses on the inlet to the baghouse, have indicated a wide distribution of flow patterns within the inlet ducts and these flow patterns vary with changes of load on the unit. It was important to make the best possible effort to determine inlet and outlet loadings of the different flue gas constituents. Also, because of the special sampling problems of both the inlet and outlet ducts, particular consideration has been given to design and re-design of equipment used to sample these ducts. Southwestern's staff at its System Lab designed and built its own manual stack sampling equipment; for example, the probes for sampling the duct are designed for vertical sampling instead of horizontal. Because of the velocities in the duct these probes are designed to prevent whipping and bending.

One effort to prevent breakage of the sampling tube was to utilize an Inconel liner instead of glass. Problems with the probe heater and condensation within the Inconel liners indicated this was a bad decision. The old probe heaters are being replaced with ones of greater dependability and capacity.

Results of the manual stack sampling are included in III A(1).

Start-up Experience

Before a start-up plan was formulated for Harrington Station baghouse, Southwestern felt it was important to seek the advice of start-up personnel at other utilities which have baghouses in operation. Individuals known to have experience in the start-up of these systems were consulted. Additionally, a literature survey was made and the recommendations of various manufacturers were studied and discussed with WFI and EPA representatives.

The following procedures were felt to be necessary to minimize difficulties during start-up:

1. orient operators;
2. check out equipment;
3. avoid dew point and acid point conditions;
4. preheat compartments;
5. condition and precoat the fabric;
6. start up with natural gas through the boiler;
7. change from natural gas to coal with flue gas going through the baghouse as quickly as possible;
8. designate specific sequence for compartments to be brought on line;
9. add compartments as load increases;

10. monitor required operating parameters during start-up and the first cleaning sequence, such as inlet and outlet temperatures, pressure drop, and opacity.

Because Harrington Station Unit 2 was capable of start-up on natural gas, the FFS was bypassed for several weeks before it was started. With all compartments isolated from the flue gas, all hopper heaters were energized for 2 or 3 days prior to start-up in order to help preheat the compartments.

During the start-up, boiler load was maintained at 200 MW with coal as the primary fuel; only the igniter natural gas was in service. Compartments 1 and 3 were initially brought into service and the first bypass damper on the west side was closed. Compartments 16 and 18 (east) were then brought into service and the first bypass damper on the east side was closed. The elapsed time between the first compartment being brought into service and the last bypass damper closed was 3 hours and 50 minutes. The effect of the FFS on opacity can be seen in Figure 1, which shows a significant decrease in opacity after the last bypass damper on each side was closed. At this point the baghouse was completely in service with the fabric being conditioned.

Approximately 3 weeks after the FFS was initially started, Southwestern was able to operate Harrington Station Unit 2 at full load with only coal in service. The unit has operated at loads consistently above 200 MW and during the peak periods it has handled 350 MW. Figure 2 shows a history of the time spent at various loads.

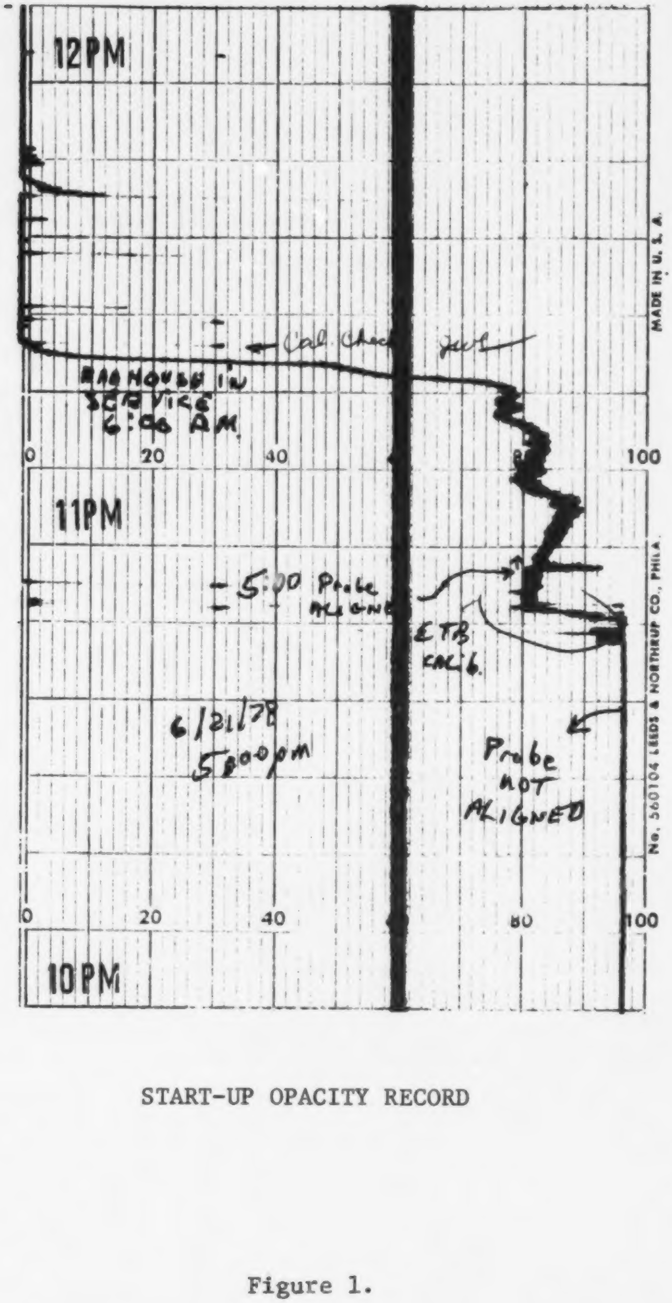
Very high ΔPs were observed shortly after start-up; the ΔP climbed quickly to 23 cm (9 inches) w.g. at full load. During subsequent months the full load ΔP steadily increased until it was in the 25-30 cm (10-12 inches) w.g. range. Judging from past performance it appears that the ΔP tends to level off a month or so after start-up. In the next few weeks, Southwestern will know what kind of ΔP will be present following rebagging of the baghouse (see discussion under B - Fabric Assessment).

Figure 3 is the plot of ΔP versus air-to-cloth ratio representative of the performance of both the east and west baghouses until February 1979, when plugging began in the west baghouse.

Testing

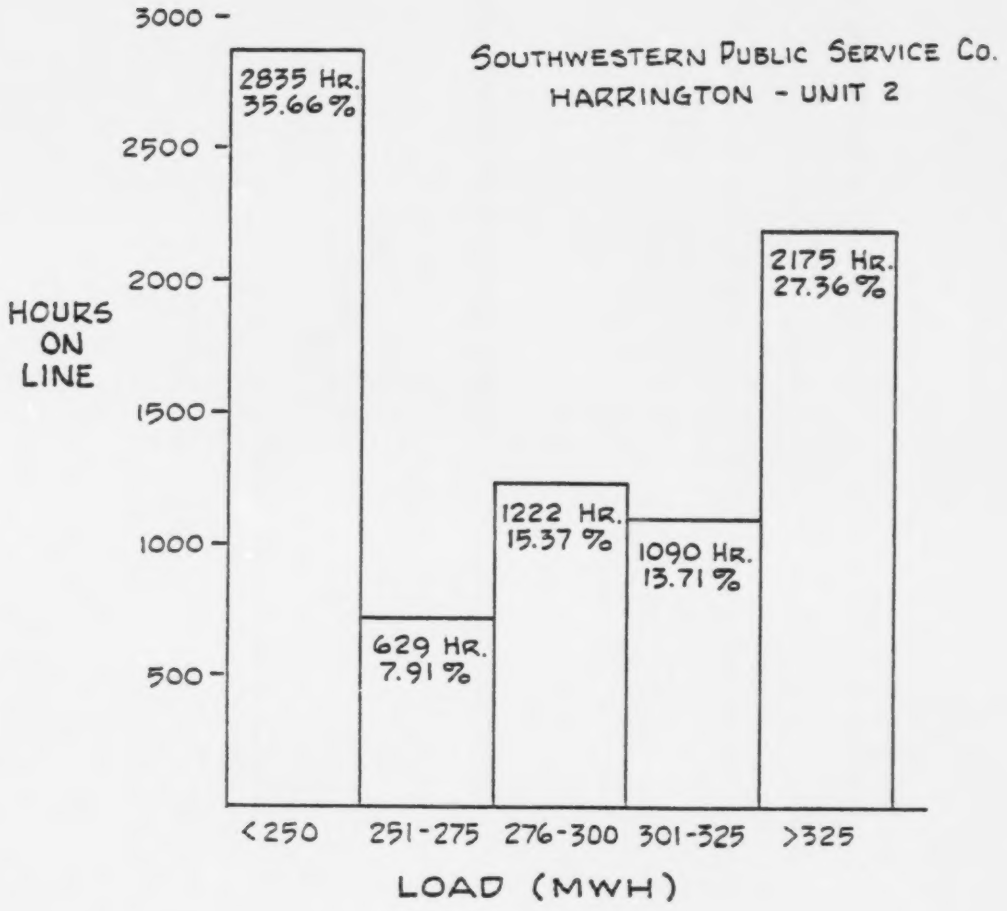
1. Air Flow Tests. The only comprehensive testing to be performed on the FFS during the first year of operation was an air flow test which was conducted by Southwestern personnel in October 1978. The primary reason for measuring the air flow was to see if the high ΔP across the baghouse was due to over-design air flow.

During the preliminary testing a large volume of turbulence was encountered on the inlet, causing the test results to disagree with the air flow measurements from stoichiometric combustion calculation. This discrepancy between calculated and measured values prompted a velocity traverse of the



START-UP OPACITY RECORD

Figure 1.



LOAD vs. TOTAL TIME
As OF 7-4-79

Figure 2.

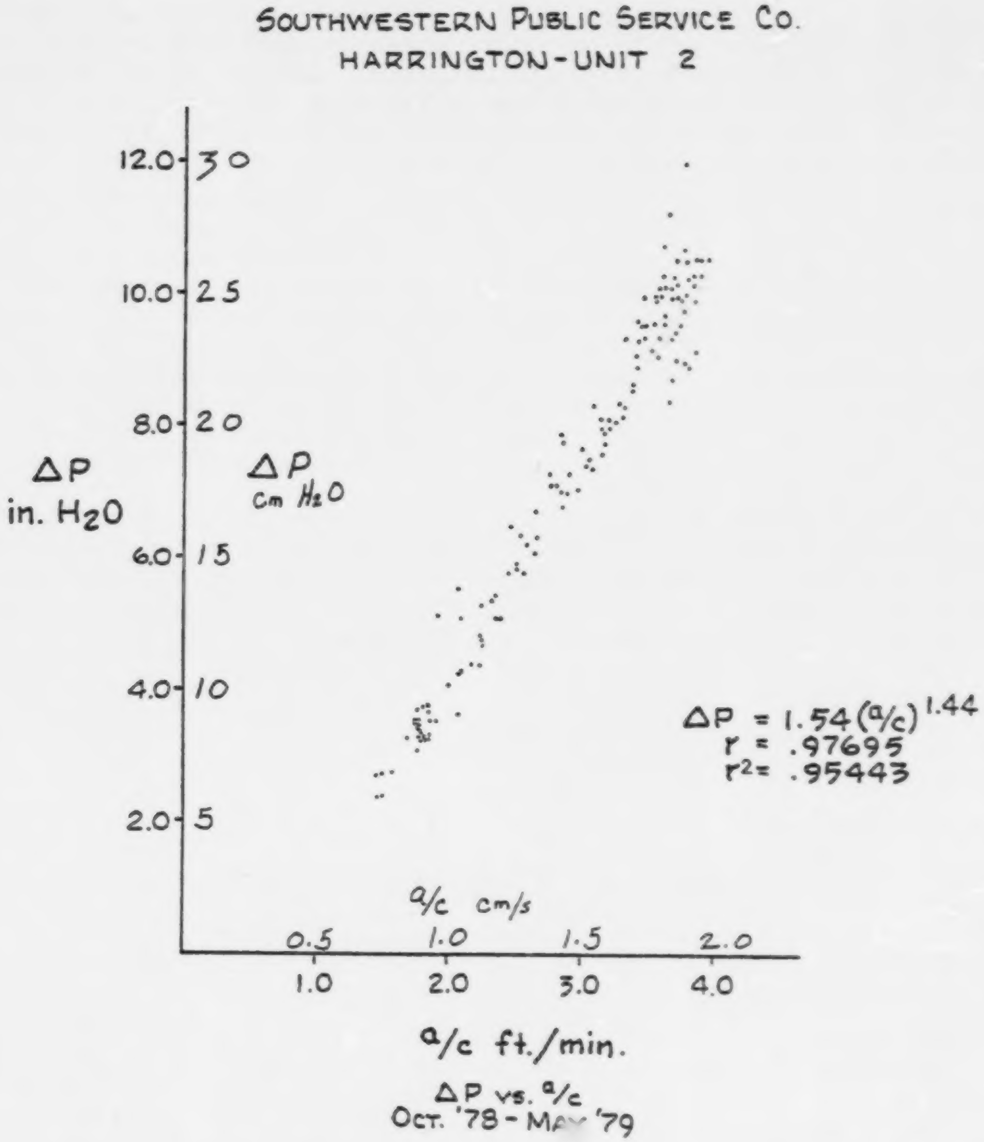

SOUTHWESTERN PUBLIC SERVICE CO.
HARRINGTON-UNIT 2
ΔP in. H_2O
ΔP cm H_2O
12.0
30
10.0
25
8.0
20
6.0
15
4.0
10
2.0
5
a/c cm/s
0.5
1.0
1.5
2.0
1.0
2.0
3.0
4.0
a/c ft./min.
$\Delta P = 1.54(a/c)^{1.44}$
$r = .97695$
$r^2 = .95443$
ΔP vs. a/c
Oct. '78 - May '79

Figure 3.

stack. The stack was selected because it met criteria specified in EPA Reference Method 2 ("eight stack diameters downstream from the disturbance"). The October air flow tests are summarized in Table 1.

2. Corrosion Testing. Southwestern, in its effort to assess the corrosiveness of the flue gases passing through the FFS at Harrington Station, placed low carbon steel coupons in the baghouse structure. Each of the 28 compartments had a coupon just inside the entrance door on the clean air side 2.1 m (7 feet) from the floor. Inlet and outlet ducts also had a coupon each. All coupons were insulated from any baghouse structural metal.

The coupons were thoroughly cleaned and weighed before installation. They were cleaned and weighed when removed in order to determine weight loss, if any. During the first year of operation, every other coupon was removed after 120 days for corrosion analyses. The remaining coupons were removed after one year's exposure (including those in the inlet and outlet ducts).

Analyses performed in Southwestern's System Lab revealed only a minor degree of corrosion after one year's exposure. The average corrosion rate was 0.006 mpy. Test results are still preliminary but Southwestern feels corrosion will not be a serious problem in this particular emission control installation.

3. The First Fabric Assessment Program. One of the goals of the FFS is to evaluate the performance of different types of fabric filters. This phase of the study was begun in June 1978, when 34 Acid Flex and 34 Tri-Treat bags from Fabric Filters were installed in compartment 22. In addition, the following bags were placed in compartment 7 in September 1978:

1	Nomex All-Spun
2	Nomex Combination
5	Crissoflex Style 446
4	Crissoflex Style 449

These bags were supplied to Southwestern by bag manufacturers for evaluation purposes.

The test bags will remain in the compartments for the duration of the study and periodically some will be removed for testing.

In addition to installation of small groups of test bags within a compartment to evaluate their endurance to the atmosphere and environment, a cleaning cycle, and potential chemical attack, it was decided that three full compartments should be fitted with test fabrics for evaluation. This decision followed after it was determined that there would be a requirement to replace the bags in the baghouse. The decision as to which bags should be used for replacement would be a matter of evaluation of a number of fabrics.

In January 1979, compartment 21 was filled with W. W. Criswell 0.28 kg (10 ounce) Style 442 Teflon-coated material; compartment 23 was filled with Fabric Filters' 0.38 kg (13.5 ounce) Style 502, Tri-Treat coated fabric. As the evaluation proceeded it was determined that a change in the shaker mechanism to clean

TABLE 1.
AIR FLOW TEST RESULTS

Traverse	O_2 %	CO_2 %	H_2O %	°C (°F)	Mol. wt. lb/lb mole	Stack Press. cm Hg (in. Hg)	Avg. ΔP cm H_2O (in. H_2O)	Velocity m/s (ft/sec)	Area m² (sq.ft)	Flue Gas Flow Rate m³/h (ACFM*)	 m³/h (ACFM**)	 m³/h (ACFM***)
SPS S Type Pitot Tube	4.8	14	9.5	168 (335)	29.05	67.23 (26.47)	2.852 (1.123)	238.0 (77.99)	31.6 (339.8)	2,750,960 (1,618,212)	2,746,882 (1,615,813)	2,679,198 (1,575,999)
WFI Std Pitot Tube	4.8	14	9.5	168 (335)	29.05	67.23 (26.47)	2.274 (0.895)	237.0 (77.79)	31.6 (339.8)	2,768,232 (1,628,372)	- -	2,696,020 (1,585,894)

* Corrected to Baghouse inlet conditions 65.18 cm (25.66 inches) Hg and 174° C (345° F) and 4.55% O_2.

** Stoichiometric calculation.

*** Measured at Stack Conditions

the bags, increasing the frequency 50 percent, resulted in noticeable improvement in fabric performance.

Another compartment of test fabrics was installed in March 1979 (compartment 20) utilizing an experimental all-filament Teflon-coated material. It was hoped that this type of fabric would have good efficiency and clean readily.

A third part of the fabric filter assessment program for selection of replacement fabric and investigation of cleaning mechanism was to review a mobile baghouse study which had been performed at Harrington Station in 1978. Over and above a number of difficulties which had to be overcome in operating this mobile unit, and maintaining general operating procedures, the study provided some interesting information. The general conclusion which could be made from the data collected indicated that Teflon-coated fabrics had a superior performance to the silicone-graphite coated fabrics in the pilot test compartment. Another interesting note resulting from the first mobile unit operation was that bags operating in the test compartment in the reverse air mode could not be successfully cleaned.

A second mobile baghouse study was initiated in the spring of 1979 to assist with the evaluation and selection of alternate fabrics to replace those in the baghouse which were experiencing accelerated failures. The following types of fabric were evaluated:

1. Fabric Filters 504-1 Acid Flex.
2. W. W. Criswell 445-04.
3. Menardi-Southern 601-Tuflex Teflon B.
4. Menardi-Southern 601-Tuflex with rings.
5. Fabric Filter 0.38 kg (10 ounce) All-Filament Teflon.

Although the final evaluation report from this second mobile baghouse testing is not complete, preliminary results indicate that fabric 1 has a better overall performance, with fabric 5 producing the least desirable results, and all of the other fabrics tested would be rated in a close middle group.

It is understood that the performance of the first mobile unit study and the second mobile unit study should be evaluated in the light of operating conditions and procedures under which the testing was performed. The results of these unit studies were used by the Company to assess fabric requirements.

A full-scale compartmental fabric testing program was initiated in an effort to determine overall performance of both durability in the baghouse environment and efficiency of particulate removal. Details of this fabric assessment are covered in III B - Fabric Assessment.

III. SECOND YEAR EXPERIENCE

A. Special Testing

A major objective of the Southwestern/EPA contract is to characterize gaseous and particulate emissions from the FFS. To do this a series of special tests was scheduled for the second year of the system's operation. Even though it was Southwestern's intent to accomplish the objectives of the tasks set forth in the contract, several problems were experienced during the operation of the baghouse which kept it from being classified as a typical or standard type of air quality control device.

These problems centered around the control of the cleaning cycle, control of the deflation pressure during the cleaning cycle, proper tension on the bags when they were initially installed, a higher than normal bag failure rate, and some indications that Harrington Station's fly ash had some unique characteristics which made predicting proper design difficult, if not impossible. Programs were developed to investigate these problem areas and attempt to come up with solutions.

During the period of investigation, limited testing of flue gas in and out of the baghouse was performed because the original intent of the research program (to investigate performance of the baghouse) was to characterize a typical operating system; therefore, many of the flue gas test plans and monitoring of gases in and out of the fabric filter have been delayed until a more typical type of operation can occur. It is felt at this time that since the rebagging of the baghouse and adjustment of cleaning cycle (finalized in July 1979) typical operation should begin in late September or early October.

With this in mind the description below indicates the performance tests accomplished by Southwestern and GCA to provide useful information.

The time and expense for performing these tests should have value to those installations experiencing the same difficulties. A review of the measures taken by Southwestern to correct the situation might be of benefit and assistance.

1. Southwestern's Performance Test. In December 1978 Southwestern performed the first series of tests to measure mass emissions of particulate, sulfur dioxides, and oxides of nitrogen. It was originally planned to sample simultaneously at five locations; however, procurement problems with equipment prohibited completion of the outlet sampling trains, and Southwestern's personnel's first-time effort in flue gas sampling of so many points at the same time, proved an adverse factor in sampling at all five locations. For particulate and SO_2 samples it was believed the test would result in better quality data if only three stations (both inlets and the stack) were sampled. The sampling procedure for oxides of nitrogen required less manpower and equipment than sampling for SO_2 and particulate; therefore, sampling for NO_x was performed at all five locations (two inlet, two outlet, one stack).

A crew of test personnel from Southwestern's power plants was assembled at Harrington Station for the first week-long series of tests. Approximately 26 stack sampling team members participated in the test program. By taking samples at three locations, rather than five, experienced personnel were able to work with the less experienced ones. As a result, personnel at all the sampling locations will have some degree of experience during future tests.

The final analyses of Southwestern's particulate, sulfur dioxide, and oxides of nitrogen samples are presented in Table 2.

The results of the inlet testing compare favorably with the theoretical inlet grain loading (the theoretical inlet grain loading is estimated and based upon generation of 80 percent fly ash). The percent fly ash has never been accurately determined but has been estimated to be between 70 percent and 80 percent.

Because of the use of an unheated probe and Inconel liner, additional deposits on the filter media gave indication of the suspected high stack grain loading. As previously mentioned, these conditions have been recognized and correction is being applied. The stack concentrations should be accurately determined during the next set of tests. The results of the NO_x testing tend to be very consistent across the baghouse. Results of the sulfur dioxide tests on the stack compare favorably with the stoichiometric calculation for sulfur dioxide. The reason for the erratic inlet results has been determined and will be corrected before the second round of special testing.

2. First GCA Special Test. More specialized tests were conducted by GCA Corporation under subcontract with Southwestern in February 1979. The gas stream was sampled at five locations (two inlet, two outlet, and one stack) for particulate, C_7-C_{17} organic compounds, C_1-C_6 organic compounds, CO_2, O_2, CO, SO_2, SO_3, NO_x, and particulate particle size distribution. Baghouse hopper ash samples were also collected.

Only preliminary results from the GCA special test are available at this time. These preliminary results are reviewed in Table 3. At a later time, when the complete report is received from GCA, the results can be better addressed. Examination of the information in Table 3 indicates that even under the best operating conditions at the time of the test, performance of the baghouse looks favorable, but it cannot consistently fulfill the new EPA proposed 13 ng/J (0.03 lb/10^6 Btu) particulate standard. Further examination and study will be necessary to evaluate the differences and inconsistencies in the SO_2 testing Method 6 and SO_3 Method 8. It is apparent at this time from the monitoring instruments and the flue gas test that the fabric filter has no effect on increasing or reducing NO_x flue gas stream.

3. Plans for Future Special Testing. The second series of special tests to be performed by Southwestern and GCA was initially scheduled for May 1979. Due to the decision to rebag the FFS (this decision is discussed under Selection of Replacement Bags), special testing has been tentatively rescheduled for October 1979. The experience gained in the first series of tests is expected to enable stack sampling personnel to conduct tests at all five sample locations as originally specified in the EPA contract.

B. Fabric Assessment

In September 1978 the Harrington Station baghouse began to experience a higher than normal failure of bags. Examination of the problem indicated that two items needed immediate attention: (1) the control of the deflation pressure during the cleaning cycle which, it was believed, contributed to the high

Table 2.

Southwestern Public Service Company

Flue Gas Tests December 1978

RESULTS OF PARTICULATE TESTING

Run Number	East Inlet g/m^3 (gr/scf)	West Inlet g/m^3 (gr/scf)	Theoretical Inlet + g/m^3 (gr/scf)	Stack ***	
				g/m^3 (gr/scf)	ng/J (lb/10^6 Btu)
* 1	5.22 (2.28)	6.27 (2.74)	5.47 (2.39)	0.121 (0.053)	45.2 (0.106)
* 2	4.67 (2.04)	5.86 (2.26)	5.13 (2.24)	0.115 (0.050)	41.7 (0.097
** 3	3.82 (1.67)	3.73 (1.63)	5.93 (2.59)	0.075 (0.033)	26.3 (0.061)

* sootblowing continuously

** not sootblowing

*** the concentrations of particulate obtained from the stack are biased high because of a reaction that took place in the unheated Inconel probe liner.

+ assumes 80 percent fly ash, no consideration for sootblowing

RESULTS OF NO$_x$ TESTING

Run Number	East Inlet Method 7 ng/J (lb/10^6 Btu)	East Outlet Method 7 ng/J (lb/10^6 Btu)	West Inlet Method 7 ng/J (lb/10^6 Btu)	West Outlet Method 7 ng/J (lb/10^6 Btu)	Stack Method 7 ng/J (lb/10^6 Btu)
1	290 (0.68)	280 (0.64)	260 (0.61)	270 (0.62)	270 (0.63)
2	310 (0.71)	290 (0.68)	250 (0.59)	270 (0.62)	280 (0.66)
3	290 (0.67)	310 (0.71)	270 (0.62)	270 (0.62)	280 (0.64)

(more)

Table 2.
(continued)

Southwestern Public Service Company

Flue Gas Tests December 1978

RESULTS OF SO_2 TESTING

Run Number	East Inlet* Method 6 ng/J ($lb/10^6$ Btu)	West Inlet* Method 6 ng/J ($lb/10^6$ Btu)	Stoichiometric ** ng/J ($lb/10^6$ Btu)	Stack Method 6 ng/J ($lb/10^6$ Btu)
1	230 (0.53)	150 (0.36)	330 (0.76)	310 (0.73)
2	250 (0.59)	140 (0.32)	360 (0.84)	340 (0.78)
3	270 (0.62)	86 (0.20)	380 (0.88)	360 (0.84)

* These concentrations are suspected of being low because of the high negative pressure pulling the absorbing solutions forward, with the absorbed SO_2 not analyzed.

** Assumes all sulfur is converted to SO_2.

Table 3.

GCA

RESULTS OF PARTICULATE TESTING EPA METHOD 5

Run Number	East Inlet g/m^3 (gr/scf)	West Inlet g/m^3 (gr/scf)	East Outlet g/m^3 (gr/scf)	West Outlet g/m^3 (gr/scf)	Stack g/m^3 (gr/scf)	Stack ng/J (lb/10^{6}Btu)
1	2.36 (1.03)	3.60 (1.57)	0.025 (0.011)	0.044 (0.019)	* *	* *
2	2.27 (0.99	3.85 (1.68)	0.016 (0.007)	0.011 (0.005)	0.021 (0.009)	7.7 (0.018)
3	3.07 (1.34)	2.75 (1.20)	0.009 (0.004)	0.018 (0.008)	0.018 (0.008)	6.9 (0.016)
4	5.06 (2.21)	3.11 (1.36)	0.009 (0.004)	0.016 (0.007)	0.027 (0.012)	10.3 (0.024)
5	3.50 (1.53)	2.34 (1.02)	0.002 (0.001)	0.005 (0.002)	0.009 (0.004)	3.0 (0.007)
6	3.11 (1.36)	5.40 (2.36)	0.011 (0.005)	0.096 (0.042)	0.039 (0.017)	14.6 (0.034)

RESULTS OF SO_2 TESTING EPA METHOD 6

Run Number	East Inlet ng/J (lb/10^6 Btu)	West Inlet ng/J (lb/10^{6}Btu)	East Outlet ng/J (lb/10^6 Btu)	West Outlet ng/J (lb/10^{6}Btu)	Stack ng/J (lb/10^{6}Btu)
2	* *	350 (0.82)	390 (0.91)	410 (0.95)	* *
4	420 (0.98)	400 (0.94)	340 (0.80)	* *	* *
6	470 (1.10)	290 (0.68)	260 (0.61)	280 (0.64)	320 (0.74)

* No data this run.

(more)

Table 3.
(continued)

G C A

RESULTS OF NO_x TESTING EPA METHOD 7

Run Number	East Inlet ng/J ($lb/10^6Btu$)	West Inlet ng/J ($lb/10^6Btu$)	East Outlet ng/J ($lb/10^6Btu$)	West Outlet ng/J ($lb/10^6Btu$)	Stack ng/J ($lb/10^6Btu$)
2	* *	260 (0.60)**	* *	300 (0.69)	* *
4	240 (0.55)	220 (0.52)	220 (0.50)	230 (0.53)	220 (0.51)
6	270 (0.63)	210 (0.48)	230 (0.53)	240 (0.55)	200 (0.47)

RESULTS OF SO_3 TESTING EPA METHOD 8

Run Number	East Inlet ppm	West Inlet ppm	East Outlet ppm	West Outlet ppm	Stack ppm
2	0.27	0.99	0.79	0.72	1.10
4	2.07	0.60	0.67	0.82	*
6	2.56	1.81	1.96	1.67	1.86

* No data this run
** Average based on three runs only

pressure drop; and (2) tension on the bag.

By October 1978 a program was begun to redesign the deflation pressure control system and bags had to be re-tensioned.

By January 1979 Southwestern was becoming concerned at the accelerated rate of bag failures. These failures were of two types; small pinhole type failures near the bottom cuff, and a few failures described as "blowouts" where a whole section of the bag would burst and fray "like a flag whipping in the wind."

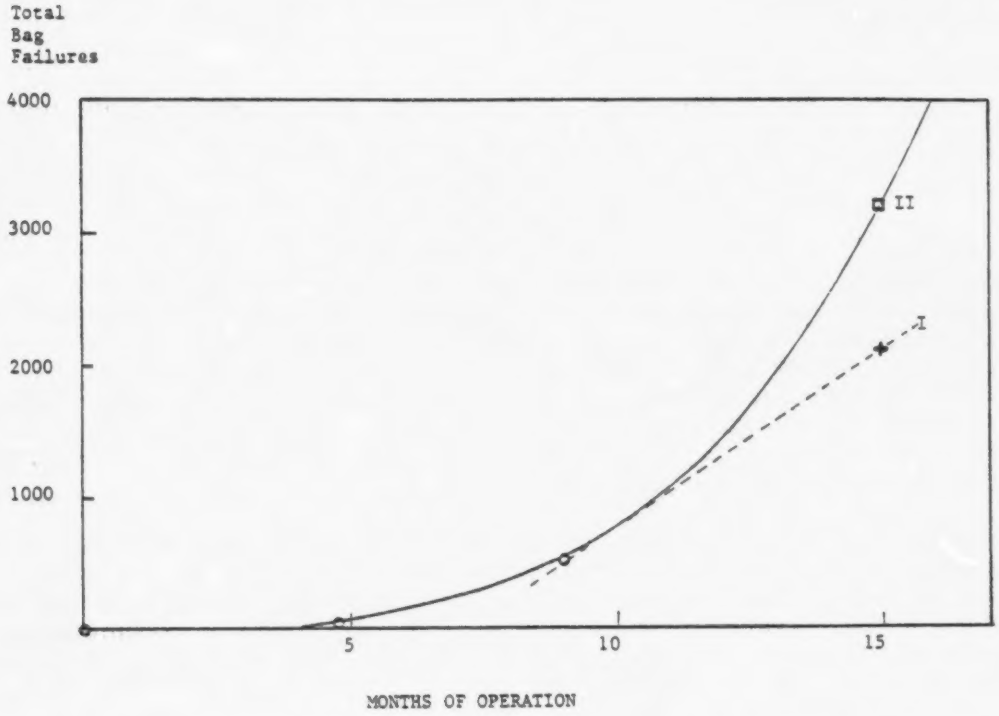
To develop an estimation of the bag failure rate to be expected during the summer the total number of failures found during outages was plotted versus service time (see Figure 4) and a simple polynomial curve performed. At this point two approaches were taken to obtain an estimate of total bag failures expected in six months of service. The first approach was to simply extrapolate the curve fit polynomial for 6 additional months of service (see Point II on Figure 4). This approach predicted ≈ 3200 failures. The second approach was to assume bag failure rate would remain constant at the present level (after 9 months of service). The curve fit equation was differentiated and the slope evaluated at 9 months' service. Point I (see Figure 4) was calculated to be ≈ 2200 failures, using this slope. Based on this information Southwestern accelerated a second fabric selection program to obtain replacement bags and have them ordered and installed by July 1979. Figure 4 indicates the extrapolated curve of bag failures which caused Southwestern's major concern.

The first bag assessment program initiated by Southwestern was used as a guideline to develop the second fabric assessment program. During the first assessment program bags had been removed periodically from compartments and laboratory tested (by a consultant). These tests corroborated Southwestern's concern about an accelerated bag failure rate which would create a problem during the 1979 summer peak.

After the decision was made to rebag the entire baghouse with new fabrics as quickly as possible, additional fabrics were obtained and installed in certain compartments for short-term testing. As mentioned previously, the EPA's mobile baghouse unit was rushed to the site and used to make an accelerated evaluation of available fabrics. Southwestern was restrained by the availability or delivery of new bags; therefore, selection was limited. Types of materials used to rebag the baghouse can be noted in Figure 5 (shown by compartments).

One of the interesting developments of the second EPA mobile baghouse study was that by adjusting the cleaning cycle and increasing the frequency of shake, a greater positive effect was noted (more positive than the differences between the fabric treatments tested). As a result of this Southwestern began to review, again, the theoretical modeling work of Dr. Richard Dennis.[1]

As a result of these two things, the decision was made to increase the



Extrapolated Estimate of Bag Failure, April 1979.

Figure 4.

WEST	BAGHOUSE
1 *	2 *
3 *	4 *
5 *	6 Menardi-Southern Teflon Test Bags
7 1 Nomex All-Spun; 2 Nomex Comb. 5 Crisoflex 446; 4 Crisoflex 449 ***	8 *
9 * (Warp In)	10 *
11 *	12 *
13 *	14 *

EAST	BAGHOUSE
15 **	16 **
17 **	18 **
19 Original bags equipped with special shaker mechanism	Fabric Filters All-filament Teflon 20
21 Criswell 442 Teflon B Test Bags	34 Acid Flex; 34 Tri-Treat Balance: Original Bags 22
23 Fabric Filters 502 Tri-Treat Test Bags	24 Globe-Albany Nomex
25 Criswell 449 Teflon B Test Bags	26 **
27 **	28 **

* Criswell 442 Teflon B, 0.30 kg (10.5 oz.) (rebagging complete).
** Criswell 449 Tri-Treat; 0.40 kg (14 oz) (rebagging complete).
*** Balance of Compartment 7: Criswell 442 Teflon B, 0.30 kg (10.5 oz.)

Fabric Installation, July 1979.

Figure 5.

frequency of the shake in compartments 21 and 23. The adjustment in frequency of shake was accomplished simply by changing the size of the shaker's drive mechanism pulley. Data collected on these two compartments, as a result of increased shake frequency, exhibited lower pressure drop by as much as 8.9 cm (3.5 in. w.g.) compared to other compartments at full flow on the baghouse.

At the time of preparation of this paper the increase in frequency of shake has not resulted in any bag failures. One problem has developed, however, on those compartments with a high frequency shake and that is the pillow blocks holding the shaker mechanism have begun to fail. An engineering redesign of these pillow blocks has already been initiated and installation of the reinforced and strengthened pillow blocks will begin soon.

Another item which should be noted about fabric assessment is that in November 1978 three Nomex bags were installed to determine if this material could survive the environment of Harrington Station conditions; i.e., low sulfur fuel and low moisture and acid dew point. After eight months of operation, examination of the Nomex bags indicates that they are still in fine condition, though slightly discolored (turning a shade of tan). Based on this experience, Southwestern has worked with the supplier and ordered and installed one compartment of treated Nomex as an additional study in the program of fabric assessment.

In addition, manometer taps were located across the outlet damper on each of the compartments to record the flow trends as well as the ΔP of each test compartment to be measured and monitored. Bags will be removed at a given interval and sent to an independent laboratory for testing. Accurate records will be maintained on bag failure rates so that at the end of the 2-year study both performance and bag life data on these fabrics will have been obtained. Certain special fabrics will also be tested in a full-scale pilot unit.

The decision to rebag the entire baghouse before July 1979 resulted in the need for developing a second start-up procedure for the baghouse and to recondition the newly installed bags. Summer peak loading conditions were becoming apparent during the period of rebagging (mid-June 1979) and the availability of bags, on short notice, required that half the baghouse be rebagged at a time.

To remain within the emission limitations required by the regulatory agency, the load on Harrington Station Unit 2 was reduced to 150 MW while one side of the baghouse was being rebagged. Because the west baghouse exhibited a higher pressure drop problem, it was rebagged first.

The start-up procedure was amended in the belief that the best way to condition a fabric is not at design air flow but at a lower flow. It was felt that lower air flows would allow a more porous, permanent matrix to establish itself over the pores in the fabric than would be possible at the very high flows Harrington Station's baghouse was designed for (air-to-cloth ratio = 3:4).

Start-up on the new fabric was accomplished by simply putting the rebagged unit on line at 150 MW and holding the load until the baghouse had gone through the cleaning cycle several times. Cleaning at a ΔP of 12.7 cm (5 in.) w.g. required in excess of 36 hours to accomplish. The load was then increased by 50 MW a day until full load (350 MW) operation was achieved.

The west baghouse was rebagged June 16, 1979 and the east on June 20, 1979. At the present time the ΔP is between 15.2 cm (6.0 in.) and 17.8 cm (7.0 in.) w.g. at full flow.

IV. SPECIAL CONSIDERATIONS

A. Air Flow

One of the most difficult assessment problems encountered on Unit 2 FSS is the measurement of gas flow through an individual compartment. As a result, operating data on the amount of gas passing through the bags is limited thereby prohibiting an analysis of potential bag life. As was mentioned earlier, in an effort to resolve this problem test compartments 19-24 were instrumented with manometer taps across the outlet damper. During the recent rebagging outage, four additional manometer taps were placed in the west baghouse (compartments 5, 6, 7, and 8) across the outlet damper. When the east baghouse was brought off the line for rebagging, three additional manometer taps were installed in compartments 25, 26, and 27. These were located exactly like those in the west baghouse.

The purpose of this instrumentation is to get an indication of the flow rate through the outlet damper. Complicating the problem is the fact that so far ΔP readings across the outlet have been in a very low range; i.e., 1.3 to 2.5 cm (0.5 to 1.0 in.) w.g.; however, it is felt that by continuously collecting the manometer readings a relative idea of flow through the test compartments can be ascertained and correlated to filter performance.

B. Pilot Baghouse

The EPA contract included a provision to exercise an option for a pilot baghouse. The EPA has elected to exercise this option and Southwestern has agreed to operate and maintain a pilot unit at Harrington Station. The objectives of this option are (1) to operate the slipstream unit under the same operating parameters as the full-scale unit, and (2) to determine if performance of the slipstream can be scaled and still represent the large operation. Additionally, optimization of the operating techniques will be determined on the pilot baghouse and applied to the full-scale unit. Future activities will include air-to-cloth ratio studies. These study areas have a high priority at EPA's research facility. Air-to-cloth ranges, in general, will be from 0.5:1 up to 3:1.

Another activity for the test facility will be to investigate the physical dynamics of fabric filtering for the purpose of determining GCA's mathematical models for the performance and operation of fabric filtering. Later other studies may examine baghouse operation at dew point, high temperature flue gas operation, and fabric cleaning techniques. Consideration may also be given to the effect of chemical injection and moisture injection.

The pilot unit is presently being installed at Harrington Station and start-up is tentatively scheduled for the first of August 1979. The facility is a WFI Model 366, Series 11.5RS DUSTUBE Dust Collector. It has two compartments and initially will be fitted with 12 Criswell Style 442 Teflon fabric filters. The bags will be 29.2 cm (11.5 in.) diameter by 930 cm (366 in.) long, complete with caps, clamps, and hardware necessary for installation. Cloth area per compartment will be 51 m^2 (549 sq ft).

V. CONCLUSIONS

One of the most apparent things found over the last year of operating experience is that there is a great deal yet to be learned about the design, selection, installation, and operation of fabric filters on large coal-fired facilities. In addition to the most common specification of air-to-cloth ratio and type of cleaning mechanism, information should be collected on physical and chemical ash properties. Pilot studies are needed on the release of fly ash cake from the fabric, and investigations should be initiated in the area of re-entrainment of fly ash back into the gas stream.

The concept that fabric filtration is an easy application and can be simply applied to any size boiler, with any type of inlet load, with any type of coal and ash products simply by scaling the units to meet the air flow requirements, is not correct according to Southwestern's experience.

Southwestern feels that fabric filtration is a developing technology and in time many of these design and operating problems will be resolved. Fabric filtration will be a demonstrated alternative for particulate control but until that time there is not justification for using fabric filtration as a control technology for all coal-fired facilities. Those in the industry and suppliers of such equipment may wish to select filtration as an alternative, but the exercise of this option should be with caution.

During the next couple of years Southwestern will continue its programs to characterize filters at Harrington Station, and will continue programs in the assessment and cleaning of fabrics. As this information is documented, it can be shared with industry, with vendors, and with regulatory groups.

References

1 "Filtration Model for Coal Fly Ash with Glass Fabrics," by Richard Dennis R. W. Cass, D. W. Cooper, R. R. Hall, Vladimir Hampl, H. A. Klemm, J. E. Langley, and R. W. Stern, GCA Corporation, EPA-600/7-77-084 (NTIS No. PB 276 489), August 1977.

START-UP AND INITIAL OPERATIONAL EXPERIENCE ON A 400,000 ACFM BAGHOUSE ON CITY OF COLORADO SPRINGS' MARTIN DRAKE UNIT NO. 6

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ABSTRACT

A fabric filter baghouse was installed on an 85 MW unit at the City of Colorado Springs' Martin Drake Power Plant. This baghouse retrofit was placed on line in September 1978. During the initial operation, some minor design and operational problems arose. Minor modifications were made to the baghouse system which eliminated these problems. The baghouse is experiencing a relatively low operating pressure drop and continues to maintain zero visible emissions.

START-UP AND INITIAL OPERATIONAL EXPERIENCE
ON A 400,000 ACFM BAGHOUSE
ON CITY OF COLORADO SPRINGS' MARTIN DRAKE UNIT NO. 6

INTRODUCTION

As a result of dwindling natural gas supplies as a source of fuel for electric generating plants, each successive boiler installation after the late 1950's was designed to burn western, low-sulfur coal. With this switch from a relatively clean fuel (natural gas) to coal, and with frequent changes in environmental regulations, the installation of air pollution control equipment was a necessity.

The Colorado Springs Department of Public Utilities' experience with air pollution control equipment is associated with installation of a first generation, cold-side precipitator with a retrofitted, sulfuric acid gas conditioner; a second generation, retrofitted, oversized, cold-side electrostatic precipitator with a sulfur dioxide gas conditioner; and a hot-side electrostatic precipitator. Each successive installation incorporated the latest technological changes dealing with the problem of collecting high resistivity fly ash at a high altitude and with semi-arid conditions. But, due to changing regulatory requirements, these units are marginal performers.

Forecasted energy growth demands and replacement of retired generating units make it a necessity to install additional generating units. Because the City of Colorado Springs is located in a valley with the Rocky Mountains in the background, visible emissions are accentuated; therefore, the particulate control equipment for these new units must not only meet air pollution regulatory requirements, but must also result in nearly zero visible emissions.

As a result of an extensive study to review the status and long-term performance of the "state-of-the-art" of particulate control technology, a decision was made to purchase and install a fabric filter baghouse collection system for the new 200 MW, Ray D. Nixon Unit No. 1, which will go on line in the last quarter of 1979.

Shortly after this decision was made, the Department of Public Utilities was sited for a violation of Colorado's opacity regulation on its existing Martin Drake Unit No. 6. Martin Drake Unit No. 6 was equipped with a cold-side precipitator of 1968 vintage with a sulfuric acid gas conditioner retrofitted in 1972. Because of the passage of more stringent air pollution control requirements and the advancement of the "state-of-the-art" in particulate control for western, low-sulfur coal-fired power plants since 1968, the decision was made to retrofit Martin Drake Unit No. 6 with a fabric filter baghouse similar in design to that of Ray D. Nixon Unit No. 1.

In March 1977, the Department of Public Utilities entered into a cooperative contractural agreement with Buell Emission Control Division, Envirotech Corporation, to perform a research and development product optimization program to evaluate the design and various materials and operational parameters on a full-scale, fabric filter baghouse for Martin Drake Unit No. 6. Martin Drake Unit No. 6 is an 85 megawatt, pulverized-coal utility boiler with a flue gas volume of 400,000 ACFM at full load.

The purpose of the research and development program is to develop a cost effective method of design and operation of a fabric filter collection system for pulverized-coal utility boilers not only to reduce particulate emissions to achieve a clear stack, but also to find an alternative to wet scrubbing techniques for the reduction of sulfur dioxide by injecting calcium and sodium compounds into the baghouse system. The overall goal is to advance the "state-of-the-art" of fabric filtration for particulate and gaseous control. The four major objectives to approach this goal are to: (1) investigate and evaluate the theoretical collection mechanisms of fabric filtration; (2) perform optimization tests on fabric filter systems; (3) investigate the effectiveness and impacts of sulfur dioxide control in a fabric filter baghouse by first injecting sodium compounds and then injecting calcium and sodium compounds in a two-stage spray drying process; and (4) develop a performance prediction model to simulate the fabric filtration process. It is felt that, in order to obtain maximum benefit from the data to be obtained, the research and development testing should be done on a full-scale basis. However, since there is a need to test the most extreme operating conditions which may irreversibly damage the full-scale unit, a pilot unit will be run in parallel. This pilot unit will allow for gathering information under the most extreme operating conditions without compromising the integrity of the entire system to function as an air pollution control device.[1]

Although the primary objective of this baghouse installation is to conduct research and development experimentation on fabric filtration systems, the remainder of this paper will address only the start-up and initial operation of the particulate collection system.

DESCRIPTION OF THE FABRIC FILTER SYSTEM

Under the scope of responsibilities of this research and development project, Buell furnished the full-size fabric filter equipment; provided technical erection supervision, start-up supervision and initial operation advisory services; and conducted performance testing and research and development program activities. The City of Colorado Springs' responsibilities were to furnish the foundations, ash handling system, induced draft fan, hopper enclosures, piping and wiring, insulation, and auxiliary equipment; erect the fabric filter system; and operate the unit during testing.

Figure 1 briefly describes the fabric filter installation. Bascially, the baghouse was designed to handle 400,000 ACFM of flue gas at 315F with a particulate inlet grain loading of 5.55 GR/ACF. The Department of Public Utilities required a design air-to-cloth ratio of 2.0:1 with one compartment out for cleaning and one compartment out of service for maintenance. The Utilities also specified the cleaning method to be reverse-air only, thus requiring anti-collapse rings in the bags. Buell responded by providing a twelve-compartment baghouse with 198 bags per compartment for a total of 2376 bags. The bags in each compartment are arranged so as to provide a three-bag reach with two walkways on the compartment floor and two in the upper part of the compartment for easy access to the bags. Each bag is thirty feet, six inches (30'6") in length and twelve inches (12") in diameter with an effective cloth area of 91 ft.^{2} per bag. This cloth area does not include the cuffs at the top and bottom of the seven anti-collapse rings.

The reverse-air system was designed to provide up to 36,000 ACFM of flow at a pressure drop of two inches (2") water gauge. A redundant reverse-air fan was provided as a backup. The reverse-air flow is controlled by an inlet louvered damper.

The nominal average pressure drop across the bags, as estimated by Buell, was determined to be four inches (4") of water gauge. The maximum pressure drop across the flange-to-flange baghouse was estimated to be six inches (6") of water gauge. The guaranteed maximum pressure drop across the system, including the breeching to and from the baghouse, is eight inches (8") of water gauge. Because Unit No. 6 is a pressurized-boiler unit, an induced draft fan was installed only to act as a booster fan for the additional pressure drop resulting from the baghouse operation. This induced draft fan was designed to provide 400,000 ACFM of flow, at 315F, at a pressure drop of eight inches (8") of water gauge. The induced draft fan is controlled by an inlet louvered damper.

Each compartment can be individually isolated for inspection or maintenance purposes while the unit is still on line. Each compartment has its own hopper, inlet poppet valve, outlet poppet valve, reinflation poppet valve, and reverse-air poppet valve. To isolate a compartment, all valves can be completely closed by removing the selected compartment from the automatic operating mode. This electrically isolates the valve actuators from the automatic cleaning cycle and closes all poppet valves. A key interlock system is incorporated into the system so that manual valve blocks must be put into position, which physically prohibits any poppet valve from opening before a key is made available to unlock the compartment doors. The two upper doors and two lower doors are then opened to cool down a compartment before entering.

All inlet, outlet, reverse-air, and reinflation poppet valves and the bypass damper are pneumatically operated. Each individual poppet valve can be operated manually at the main control cabinet in the boiler, turbine-generator control room or at local control stations in the baghouse itself. For any compartment to be manually operated, the master compartment control switch must be put into the manual mode. This will allow operations at either the local control station or the main control panel. In normal operation, all master compartment control switches will be placed in the automatic mode. This places the operation of all compartment poppet valves under the control of a solid-state programmable, microprocessor control system. The primary purpose of this control system is to initiate and sequence each compartment through a cleaning cycle, which is initiated through a flange-to-flange pressure drop signal. This preset pressure drop is 4.5 inches of water gauge. Therefore, when the pressure drop across the baghouse reaches 4.5 inches of water gauge, a cleaning cycle is triggered. Each compartment is reversed-air cleaned for about 20 seconds at a flow rate of 22,000 ACFM (A/C equals 1.22:1) in sequence from compartment No. 1 through compartment No. 12. The entire cycle takes approximately fifty-five minutes. The microprocessor will also trigger a trip-to-bypass if it receives a preset flange-to-flange pressure drop which has been determined to be too high to maintain the integrity of the baghouse system. Other safety features include trip-to-bypass functions which will protect against high or low operating temperatures. The baghouse controls are also interconnected with the boiler permissive system to provide for safety under emergency boiler trip conditions.

START-UP OF THE FABRIC FILTER BAGHOUSE SYSTEM

The start-up fuel for Martin Drake Unit No. 6 is natural gas. Because natural gas is free of particulate and sulfur, and because there is a bypass on the baghouse system, the decision was made not to pre-coat the fiberglass bags before initial operation.

The flue gas was allowed to go through the bypass until a stable boiler operation was established with the flue gas temperature well above the moisture dew point. Once this stable operating condition was achieved, this warm dry flue gas was allowed to pass through the compartments by opening certain compartment inlet and outlet poppet valves and closing of the bypass dampers. As the flue gas flow rate was increased, more compartments were put on line to maintain a maximum air-to-cloth ratio of 2.0:1. Once all compartments were put on line, natural gas firing was allowed until the entire baghouse was fully expanded and allowed to grow to its fullest extent.

On September 15, 1978, one coal mill was put into operation and the first fly ash laden flue gas entered the baghouse. At that moment, the opacity surged to approximately 60%. The opacity rapidly decreased so that after approximately ten minutes, the opacity was down to 20% and after thirty minutes, the opacity was 10%. After the first twenty-four hours of operation, there were practically zero visible emissions being emitted from the stack. The pressure drop during the initial operating stages across the flange-to-flange was undetectable.

The first cleaning cycle was triggered approximately twenty-four hours after start-up. A momentary opacity excursion was detected up to approximately 40% when the first compartment came on line after completing its reverse-air cleaning. When the succeeding compartments went through this initial cleaning cycle, momentary opacity excursions also resulted, but declining in intensity with compartment No. 2 at approximately 10% to compartment No. 12 at 1%. Subsequent cleaning cycles show momentary opacity excursions of 10% after the first week of operation, 5% after the second week of operation, 2% after the third week of operation, and zero visible emissions after the first month. It should be noted that these momentary excursions only occurred during that part of the cleaning cycle when the first two compartments were put back into service after reverse-air cleaning. At all other times during its operation, there were zero visible emissions being emitted from the stack.

There was no detectable pressure drop for the first few days of operation. After three days, the flange-to-flange pressure drop was approximately 1.0 inch of water gauge following a cleaning cycle. This pressure drop following a cleaning cycle is presently 3.0 inches of water gauge. The time period from the end of one cleaning cycle to the beginning of another is approximately two hours. This is at full load operation with all twelve compartments in service.

INITIAL OPERATIONAL PROBLEMS

The major operational difficulty with the baghouse was associated with the pneumatic system that operates all the poppet valves. The original system included a 10 CFM dryer and the piping served as the compressed air reservoir. This proved to be too small and too restrictive for the proper operation of the baghouse. Also, last winter Colorado Springs experienced its coldest season in decades. As a result, there were many icing problems encountered which inhibited proper operation of the baghouse, especially during the cleaning cycle. To remedy these situations, the air drying system was enlarged to 100 CFM with added air receiver to maintain a constant pressure of 82 PSI. Also, filters, lubricators and regulators were installed at every one of the 49 actuators to insure that clean, lubricated air at a constant pressure would be provided. Since the installation of this additional equipment, the problems with the pneumatic system have ceased to occur.

OPERATIONAL COSTS

Since the baghouse has only been on line ten months, it is difficult to arrive at any annual operational and maintenance costs that will be indicative of this system. Since start-up, there have been only two bag failures. This is about 0.084% of the total bags installed. The first bag failure was caused by a sharp object that cut the bag fibers. This most likely occurred during an inspection of the baghouse during the annual boiler outage. The second failure resulted from fly ash escaping from the first bag leak and impinging on a nearby bag and causing another leak.

The average operating cost seen to date is approximately 0.03 mills/KWH.

CONCLUSION

In conclusion, the Martin Drake Unit No. 6 fabric filter baghouse is a very successful particulate control system. There are no visible emissions detectable during any phase of normal operation. Actual test results indicate collection efficiency in the range of 99.89% to 99.95%, but the emission rates were constant at about 0.0013 GR/ACF and 0.0046 pounds per million Btu. The cause for the different efficiencies is due to the variations in the inlet grain loadings during the different tests ranging from 1.2 GR/ACF to 2.6 GR/ACF.

Finally, the pressure drop across the baghouse is averaging about 3.75 inches of water gauge. The baghouse will initiate a cleaning cycle at 4.5 inches of water gauge and clean down to 3.0 inches of water gauge. The time from the end of one cleaning cycle to the beginning of the next cleaning cycle is approximately two hours.

As a result, the City of Colorado Springs' Department of Public Utilities feels it has a highly efficient fabric filter system operating at a relatively low pressure drop.

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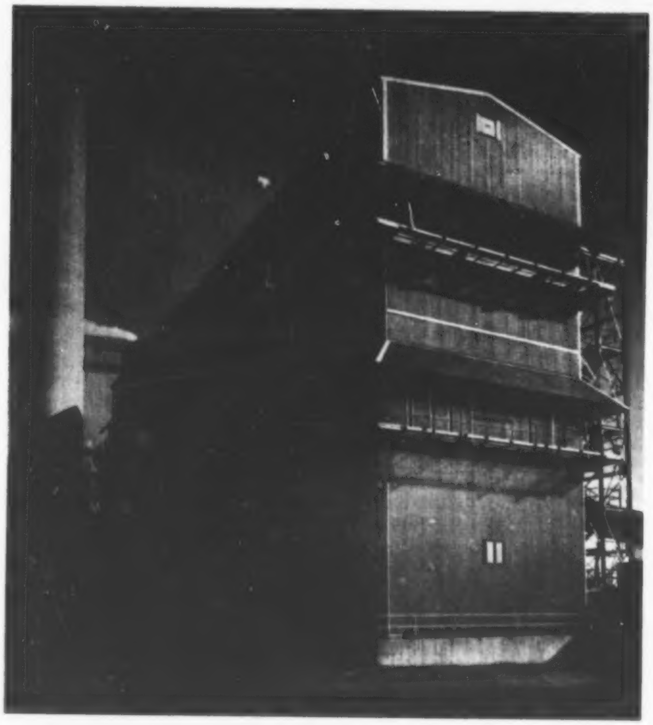
Fly Ash Application At City of Colorado Springs



Buell structural baghouse for an 85 megawatt pulverized-coal-fired power boiler at the City of Colorado Springs Martin Drake Power Plant. Operational September 1978.

Design Criteria

Gas volume	400,000 ACFM
Normal gas temp.	315°F
Max. allow. temp.	550°F
Min. allow temp.	250°F
Coal fired, lb/hr	93,400

Coal Analysis

Moisture	13.4%
Ash	15.6%
Sulfur	0.3%
Volatile matter	29.5%
Fixed carbon	40.9%
BTU per lb.	9,300

Performance

Inlet Gr/ACF	1.84
Outlet Gr/ACF	0.002(99.89%)

Buell Project Scope

Research and development program.

Complete process and system design engineering responsibility.

Material supply includes all material from inlet flange of baghouse to outlet flange of baghouse with all related operational instruments and controls.

Equipment Specifications

Overall dimensions	174′ x38′ x84′ high
No. of compartments (ea. with hopper)	12
Hoppers, outlet manifold	1/4″ A-36 steel
Casing, inlet manifold	3/16″ A-36 steel
Bag cleaning method	reverse air
Bag material	glass fiber with Teflon coating
Bag diameter	12″ nominal
Bag length	30′-6″
Air-to-cloth ratios: Gross	1.85:1
Net	2.01:1
Total no. of bags	2,376 (198/compartment)
Electronic controls	solid state design

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REFERENCES

[1] Ronald L. Ostop and Larry A. Thaxton, "Optimization of Material, Design and Operational Parameters Associated with a Full-Scale 400,000 ACFM Fabric Filter Baghouse on the City of Colorado Springs' Martin Drake Generating Unit No. 6," presented before the 40th Annaul Meeting of the American Power Conference, April 26, 1978, sponsored by the Illinois Institute of Technology. Chicago, 1978.

DESIGN, OPERATION, AND PERFORMANCE TESTING OF CAMEO NO. 1 UNIT FABRIC FILTER

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ABSTRACT

A Carborundum fabric filter was retrofitted to the Cameo No. 1 unit in 1978. Cameo Station, owned and operated by Public Service Company of Colorado, is near Grand Junction, Colorado, and No. 1 unit (22 MW) was first placed in service in 1958. The purchase contract for the fabric filter was written on July 2, 1976, but due to problems in obtaining an emission permit from the State of Colorado, actual construction did not begin until February, 1978. The fabric filter, designed with 1.92 gross air to cloth ratio and reverse air, was placed in service December 18, 1978. This paper covers the design aspects, construction features, startup procedures, and acceptance testing.

DESIGN, OPERATION, AND PERFORMANCE TESTING OF CAMEO NO. 1 UNIT FABRIC FILTER

INTRODUCTION

Public Service Company of Colorado's (PSCC) Cameo Station is located 14 miles east of Grand Junction on the Colorado River. The No. 1 unit (22 MW) was placed in service in 1958, and the No. 2 unit (44 MW) was placed in service in 1963. The No. 1 unit consists of a Babcock & Wilcox integral boiler, front fired, with 215,000-pounds-per-hour capacity. Steam conditions are 890 psig and 910° F. The design flue gas flow is 110,500 acfm at 310° F. The unit was originally designed for either coal or natural gas firing, and the only air pollution control device was a mechanical dust collector.

In April 1970, the No. 1 unit was committed to gas firing only as a pollution control measure. Coal was to be used as the fuel only if a system electrical emergency existed and natural gas was not available. As gas supplies dwindled and the unit was required to fire coal more and more frequently, it became apparent that either the unit would have to be retired or a particulate control device would have to be installed to clean the boiler flue gas.

Coal contracts for Cameo Station were in a state of flux in 1974 and 1975; and, therefore, the long-term coal supply was unknown. The selection and engineering design of an electrostatic precipitator under this condition would be very difficult. Also, economic evaluations indicated the cost of a fabric filter to be nearly equal to the cost of an electrostatic precipitator.

Field trips to Colorado-Ute's Nucla Station in Nucla, Colorado, and to Pennsylvania Power & Light's Sunbury Station convinced PSCC's operating and engineering personnel that fabric filters were a viable pollution control technology, especially when burning low-sulfur western coals. The performance of each fabric filter installation visited indicated that a clear-stack status was possible with fabric filter technology.

DESIGN

In mid-1975, a specification for a fabric filter was prepared and was issued in November 1975. The basic design criteria for the fabric filter as specified is included in the following table:

Table 1. FABRIC FILTER SPECIFICATION

Gas Volume/Baghouse - acfm		170,000
Temperature - °F.		290
Approximate Inlet Loading - gr/acf		0 - 4 (2.79 calculated)
ΔP across Baghouse (2 Compartments Out) (Max.)		7.0
Bag Spacing (Between Bags)		2"
Abrasion Protection		Thimbles Above & Below Tube Sheet
Rings per Bag		5
Bag Reach (to Center of Farthest Bag)		36"
Air/Cloth Gross	Without Reverse Air	2.0/1
Air/Cloth Net Two Compartments Out		2.3/1

The fabric filter cleaning was specified to be by reverse air only. The above design criteria were to be met while burning coal from three suppliers: Energy Fuels Corporation, P & M Coal Company, and Cambridge Mining Corporation. The origin of the coal, therefore, would be either Routt County or Mesa County, Colorado. The specification did not give analyses from the various coal suppliers but specified minimum and maximum values. The proximate analyses were shown in the specification as follows:

Table 2. COAL ANALYSES

	Minimum (%)	Maximum (%)
a. Moisture	4	17
b. Ash	4	18
c. Volatile matter	31	36
d. Fixed carbon	43	51

The ultimate analyses of the above coals were also given as:

a. Hydrogen	4	6
b. Carbon	58	68
c. Nitrogen	1	2
d. Oxygen	9	21
e. Sulfur	0.3	0.7
f. Ash	4	18

The heating value (as received) was 9,200 Btu minimum; 12,000 Btu maximum. The specification also listed ash composition and again was on a minimum-maximum basis.

A new coal supplier has been added since the specification was issued. The Bear Coal Company is now supplying more than 80 percent of the coal for Cameo Station. This coal falls within the minimum and maximum values as listed in the specification.

A particle-size distribution test was performed on Cameo No. 1 at the inlet to the mechanical collector for the specification. The results are listed in the table below.

Table 3. PARTICLE SIZE DISTRIBUTION

Particle Size (microns)	Percent (%) by Weight Finer Than Particle Size Shown
1.4	3.88
2.35	9.06
4.7	22.01
7.6	33.37
10.5	44.62
17.2	65.34
20.9	73.80
23.3	77.39

FABRIC FILTER SELECTION

The specification was issued to seven bidders. The evaluation of the five proposals received was based not only on the bid documents but also on the total evaluated cost, including the estimated annual operating and maintenance expense. Carborundum was the successful bidder and a purchase contract was issued to them July 2, 1976 to design, supply and erect the fabric filter on Cameo No. 1 Unit.

The table below lists the actual design parameters of the fabric filter as supplied by Carborundum:

Table 4. FABRIC FILTER DESIGN PARAMETERS

Gas Volume/Baghouse - acfm		170,000
Temperature - °F.		290
Approximate Inlet Loading - gr/acf		2.79 calculated
Outlet Loading - gr/scfd		0.007
ΔP Across Baghouse (2 Compartments Out)		6.2"
Compartments - Number		8
Bags per Compartment		240
Bag Material		Teflon Coated Fiberglass
Bag Dimensions		8" x 22'6"
Bag Spacing (Between Bags)		2"
Abrasion Protection		Thimbles Above & Below Tube Sheet
Rings per Bag		5
Bag Reach (to Center of Farthest Bag)		36"
Tension (pounds)		40-60
Air/Cloth Gross	Without Reverse Air	1.92/1
Air/Cloth Net One Compartment Out		2.20/1
Air/Cloth Net Two Compartments Out		2.57/1
Fabric Filter Size		
Length		69'
Height		54' 8"
Width		33' 4"

A schematic of the general arrangement of the Cameo No. 1 fabric filter is shown in Figure 1.

The filter bags as supplied by Carborundum have the following specification:

Table 5. FILTER BAGS

Manufacturer	Carborundum
Fabric	Fiberglass
Treatment	10% DuPont Teflon B
Weave	Twill
Count	54 x 30
Yarn	
Warp	150 - 1/2
Fill	150 - 2/2
Weight	9-1/2 oz/sq yd
Permeability	65 - 80 cfm/sq ft
Textured Surface	Inside

The fabric filter as supplied by Carborundum has two reverse air fans. The reverse air fans have a gas-flow capability of 22,000 acfm with a static-pressure capability of 12 inches of water. The unit is provided with two bypass poppet-type dampers. All dampers (including inlet, reverse air, outlet, and bypass valves) are installed with electric-motor-driven operators. The control system located at the base of the fabric filter is an electro-mechanical relay-type control system with complete controls for each compartment. The cleaning cycle can be initiated by (a) time of day, (b) total pressure drop across the fabric filter, (c) lapsed time from last cleaning cycle, and (d) manually. One compartment has an observation port installed at the lower and upper walkway levels. Although this port helped to determine the bag movement when the reverse air fan was taken out of service, PSCC would not install observation ports on other fabric filters. The fabric filter was not insulated between compartments nor between the compartments and the inlet and outlet ductwork.

The I.D. fan was tested and found to be sufficient in both flow and static pressure characteristics; therefore, no fan modifications were required.

The Company encountered problems when attempting to obtain a permit to construct. Therefore, the engineering and procurement of the fabric filter were put on "hold" October 14, 1976. Following eleven (11) months of negotiations, a permit to construct was obtained September 16, 1977. On this same day, Carborundum was authorized to resume engineering on the project. In February 1978, the engineering was completed and construction of the fabric filter commenced with the pouring of the foundations. Carborundum moved on site and started construction in July 1978, and the fabric filter was completed and placed in operation December 18, 1978.

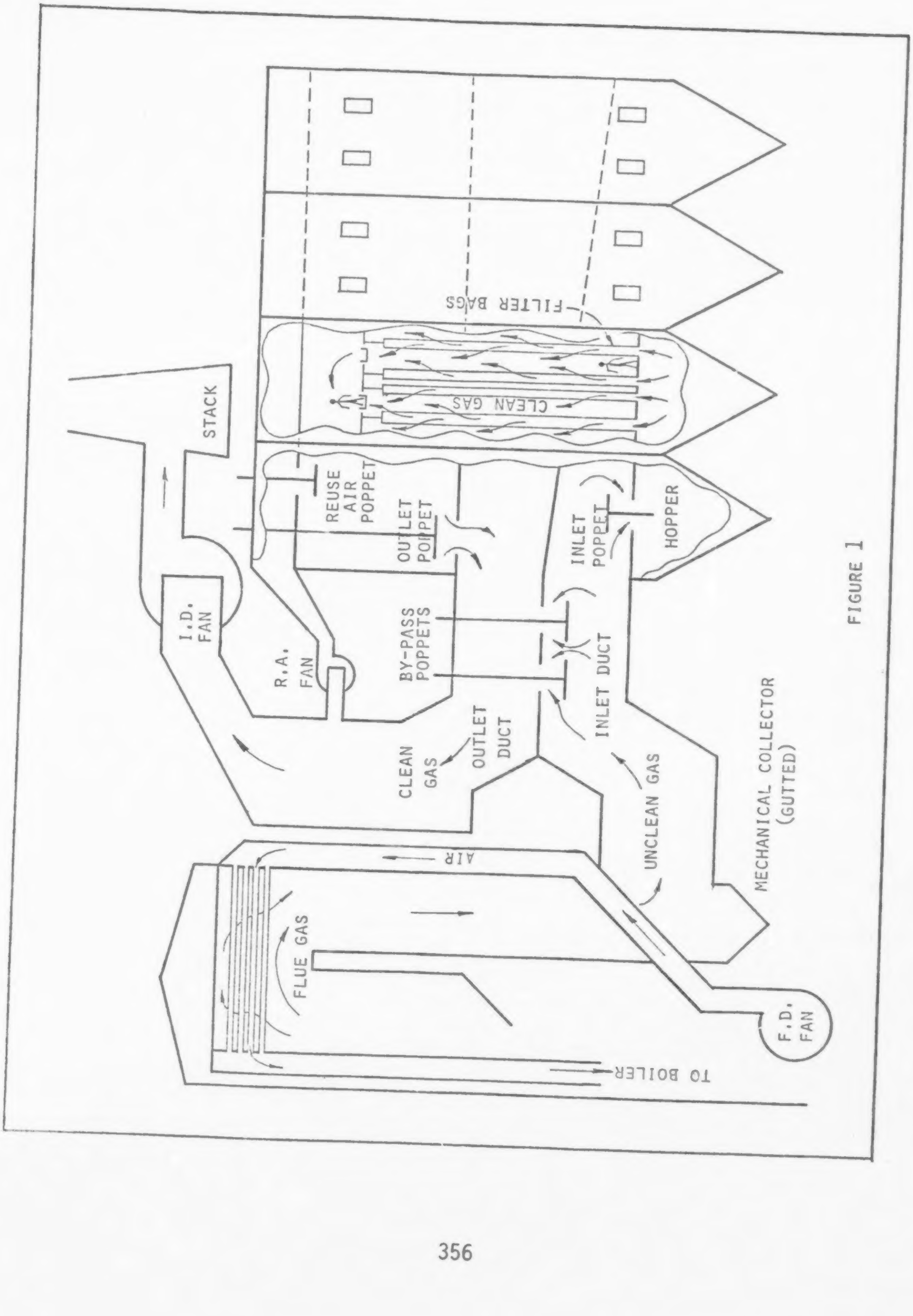
STACK
I.D. FAN
R.A. FAN
REUSE AIR POPPET
OUTLET POPPET
BY-PASS POPPETS
CLEAN GAS
OUTLET DUCT
INLET DUCT
INLET POPPET
HOPPER
UNCLEAN GAS
MECHANICAL COLLECTOR (GUTTED)
AIR
FLUE GAS
F.D. FAN
TO BOILER
CLEAN GAS
FILTER BAGS

FIGURE 1

The condenser cooling water for Cameo Station comes from the Grand Canal. The canal is taken out of service in March and October for maintenance and inspection. During the canal outage the plant condenser cooling water is provided by a spray pond. During the October 1978 outage the No. 1 unit was taken out of service for 27 days to make the required inlet and outlet duct connections. Blanking plates were installed in the inlet and outlet duct and the No. 1 unit returned to service on the bypass. The unit was then taken off the line for five days to remove the blanking plates prior to the December 18 start-up date.

The start-up procedure used to place the fabric filter in service was accomplished as follows: The No. 1 unit was started up on natural gas and raised to full load capabilities with the bypass poppet valves in the open position. After attaining an air-heater-outlet temperature of 270° F., the bypass poppet valves were closed, and, while still operating on natural gas, the fabric filter was heated to within 10° of the boiler outlet temperature. After attaining the desired fabric-filter temperature throughout, which took approximately six hours, coal was added to the boiler through one of the coal mills. This mill was then fully loaded, and the natural gas equivalent to that mill was removed from the boiler. The second mill was then placed in operation, and the natural gas was completely removed from the boiler. The differential pressure from the dust loading took approximately 12 hours to increase to the desired four inches of water pressure. At this time, the reverse-air fan was started, and the first cleaning cycle was initiated. After being cleaned the first time, the fabric filter indicated a differential pressure of approximately one inch. The differential pressure was again allowed to build up before the next cleaning cycle was initiated, and this procedure continued, cleaning only as the differential pressure built to 4-1/2 inches of water.

At the end of each cleaning cycle, it was noted that a visible plume appeared at the stack. It was apparent that the bags were being "overcleaned" to the extent that dust was penetrating through the fabric. As a result of this penetration, the decision was made to try cleaning without the reverse-air fan. All cleaning since the first week of operation has been without the reverse-air fan in operation. The cleaning cycle presently is based on the 4.5 inches differential, during which a cleaning cycle is initiated, and each compartment is sequenced through its cleaning cycle. At the end of the cleaning cycle, the differential pressure is 1-1/2 to 2 inches of water. This is allowed to build over a period of eight to 10 hours back to 4-1/2 inches of water, when another cleaning cycle is initiated. The reverse-air fans, therefore, have not been used since the first week of operation.

The initial two weeks of operation with the fabric filter were followed by a routine two-month annual outage of the No. 1 unit. During this outage, a thorough examination of the fabric filter indicated minor leaks through the retaining clamps that hold the bags on the thimbles. These were tightened as needed and the compartments vacuum cleaned. After the unit was put back in service March 4, 1979, the operating personnel removed one compartment from service during each graveyard shift to allow for an inspection during the day shift. The major problem encountered was loose clamps around the cuff of the bag where it attaches to the thimble. As leaks were found, the clamps were tightened; and the compartment was vacuumed in order to make the next visual inspection easier. The removal of one compartment each night continued for two months. Now, however, this inspection cycle has been increased to once a month.

Each compartment has two lower access doors and two upper access doors. Air leakage at the door seals was noted by rust indications on the inside of the door facings. An ultrasonic leak detector was used to determine exactly where the leaks were, and hinge adjustments were made until these leaks were eliminated. No other noticeable maintenance problems or leaks have been encountered in the four months since the return to service.

PERFORMANCE CRITERIA AND ACCEPTANCE TESTING

The guaranteed performance stipulated in the specification states that the fabric filter shall remove the particulate emission from the Company's steam generator to a maximum of seven-thousandths grain per standard cubic foot (0.007 gr/scf) of flue gas measured at the fabric filter outlet on a dry basis under the following simultaneous conditions: (a) handling actual gas volumes over the entire range of the steam generator operation, (b) burning coal with a maximum of 18 percent ash, (c) handling ash in the ash hoppers, (d) isolating any one compartment of the baghouse in a cleaning cycle, (e) isolating any other compartment for maintenance, and (f) blowing soot in the boiler or air heater.

The conformance test (EPA Method 5) was used to determine the actual acceptance of the fabric filter. This test was conducted within 180 days after completion of the fabric filter. Conformance testing was done, but, since one test was more than 0.007 gr/scf, the conformance testing was repeated. Carborundum was asked to optimize the operation of the fabric filter and to check for any bypass leakage or other problems that might cause nonconformance. Welding beads were found on the bypass poppet valve, and minor leakage was occurring. An unwelded seam separating the inlet from the outlet duct also was found and repaired. The second set of conformance tests was completed June 5 and 6. The average outlet grain loading of these tests was 0.0053 gr/scfd. The fabric filter has now been accepted by PSCC as having met the performance criteria of the purchase contract.

An Environmental Data Corporation performance monitor is installed in the stack on Cameo No. 1 unit. This instrument which monitors opacity, NO_x, SO_x, and percent excess oxygen, was transferred to Cameo from PSCC's Comanche Station near Pueblo. The opacity presently is reading 2 to 4 percent. Only the opacity monitor is required by regulation; however, PSCC and EPRI presently are engineering a dry alkali injection system. The Company will conduct a series of tests to evaluate the capability of nahcolite, trona, and/or sodium bicarbonate in this system as a sulfur dioxide removal mechanism. The tests are to be conducted the latter part of this year.

Public Service Company of Colorado is to date very pleased with the operation of the Carborundum fabric filter on the Cameo No. 1 unit. The unit has been operating with a clear stack since the fabric filter went into operation. Because of this, PSCC has installed a fabric filter at its Arapahoe Station in Denver and is engineering such filters at two other coal-fired stations.

EXPERIENCE AT COORS WITH FABRIC FILTERS - FIRING PULVERIZED WESTERN COAL

By:

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ABSTRACT

Coors has been using a fabric filter unit since December, 1976, to control emissions from the Boiler No. 4 pulverized coal fired unit, rated at 250,000 lbs./hr. steam.

Pressure drop, bag life, etc., on this shake-deflate 8 module filter is presented. Data from emission tests is reviewed and discussed.

The low pressure pulse-jet type fabric filter being installed on the new Boiler No. 5 is discussed briefly. This 12 module unit is designed for 320,000 ACFM and an air to cloth ratio of 5.5 to 1.

EXPERIENCE AT COORS WITH FABRIC FILTERS - FIRING PULVERIZED WESTERN COAL

INTRODUCTION

Based on energy availability and on cost projections, Coors made the decision in 1974 to install coal firing capability on the Boiler No. 4 unit which was under construction at that time. Electrostatic precipitators, scrubbers, and fabric filters were evaluated carefully for emission control devices. The fabric filter approach was ultimately selected because it was felt that it would do the best on a continuous basis of removing particulate and achieving a low opacity stack. The fabric filter unit selected went into service in December, 1976, and has been operating successfully for the last 2 1/2 years.

EQUIPMENT DESCRIPTION

Boiler No. 4

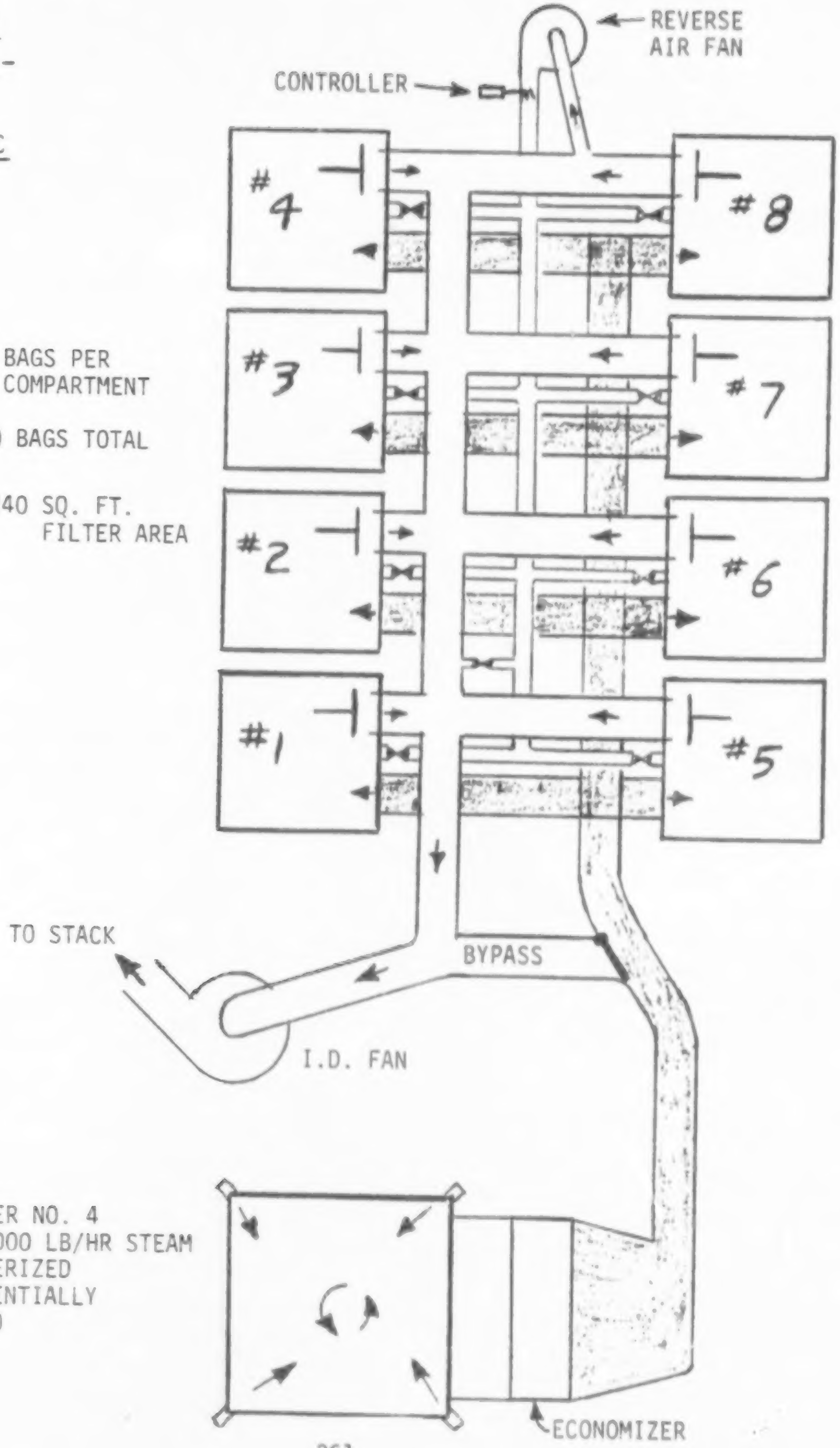
The 250,000 lb./hr. steam generator is a tangentially fired pulverized Combustion Engineering, Inc. VU-40 unit. Pulverization of the coal is accomplished by two Raymond RB-573 bowl mills. At the rear of the boiler, flue gas is cooled to approximately 340° F by a fin tube boiler feedwater economizer. There is no combustion air preheater in the normal sense on this unit.

The basic arrangement of the baghouse, boiler, baghouse bypass, I.D. fan, etc., is illustrated by the schematic of Figure 1.

Fabric Filter

The fabric filter or baghouse on the Boiler No. 4 unit is a Wheelabrator-Frye, Inc. shake-deflate cleaning type unit and operates at a typical flue gas volume of 170,000 ACFM at 340° F when the boiler is at rated load. The baghouse has 8 compartments with 180 bags per compartment for a total of 1,440 bags. The bags are 8 inches in diameter and 22 feet long and do not have rings. (The total filter area is 66,240 square feet.) The fabric description is as follows:

FIGURE 1 BAGHOUSE - BOILER SCHEMATIC



180 BAGS PER
COMPARTMENT

1440 BAGS TOTAL

66,240 SQ. FT.
FILTER AREA

BOILER NO. 4
250,000 LB/HR STEAM
PULVERIZED
TANGENTIALLY
FIRED

Material	Woven Glass
Finish	Silicon Graphite
Weave	3 x 1 RHT
Thread Count	66 x 30
Permeability (new)	45 - 65
Weight	10.5 oz./sq. yd.

Initially, one compartment of W. W. Criswell's Teflon B finished bags and one compartment of Cris-O-Flex finished bags were installed. These were removed after a few months of operation when it was discovered that the inservice permeability was much lower than with the silicon graphite finished bags.

Each compartment has a 36" diameter manually operated butterfly valve at the inlet, a 42" diameter cylinder operated poppet valve at the outlet, and a 20" diameter cylinder operated butterfly valve for reverse air. The single reverse air fan has a parallel blade damper (20" x 24") with an automatic controller on it set to accomplish a reverse ΔP across the bags of at least 0.5 inches W.G. but not more than 1.0 inches W.G. during the reverse air mode of the cleaning cycle. The automatic controller was not added to the damper until July, 1977.

Bags are located on 9" centers with a three bag reach from the one foot wide internal walkways. The access door to the bottom elevation is 24" x 60" and the access door to the upper elevation is 20" x 48".

The wall between compartments is insulated as well as all external areas of compartments, hoppers, and ducts. Each bottom hopper has a series of plate type thermostat controlled heaters (5.6 KW per hopper).

The cleaning cycle used on this unit is shown graphically by Figure 2. The baghouse is cleaned only as necessary when the ΔP rises to the designated setpoint for cleaning. When a clean mode is initiated, all eight compartments are cleaned one at a time in the sequence of 1, 2, 3, 4, 5, 6, 7, and 8. It takes 3 minutes per compartment, or 24 minutes total, to get through all eight compartments.

PRESSURE DROP CHARACTERISTIC

The pressure drop across the baghouse has been found to be dependent upon the boiler steaming rate, type of coal being burned, quality of boiler operation, and quality of baghouse operation. In general, experience has shown that the typical operating pressure drop for this unit is as illustrated by the shaded area of Figure 3. Roughly one inch of this total baghouse pressure drop can probably be attributed to inlet valve, outlet valve, and duct

Figure 2

BAG CLEAN CYCLE SEQUENCE
BOILER NO. 4 BAG HOUSE
(8 MODULES TOTAL CLEAN TIME = 24 MIN.)

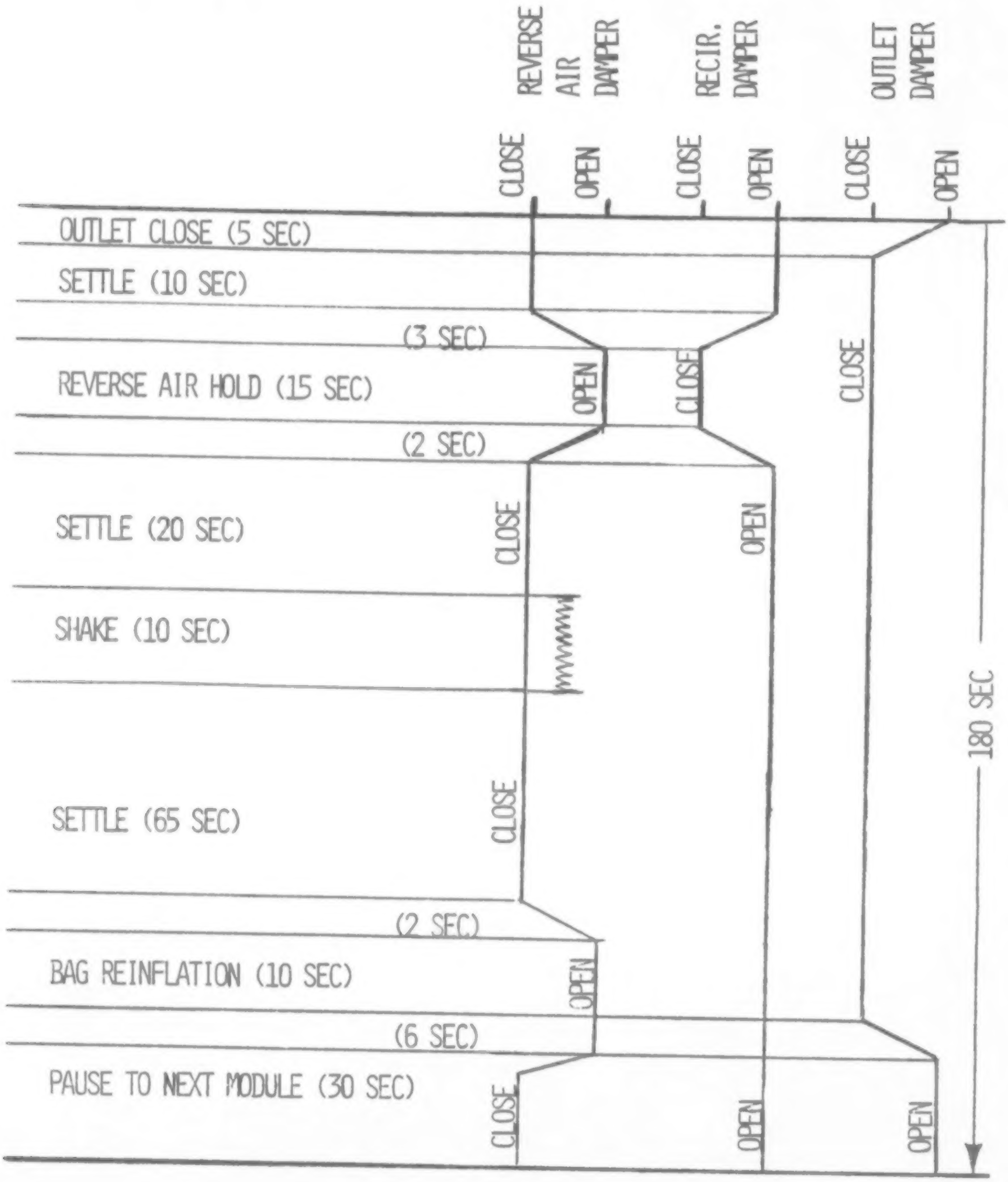
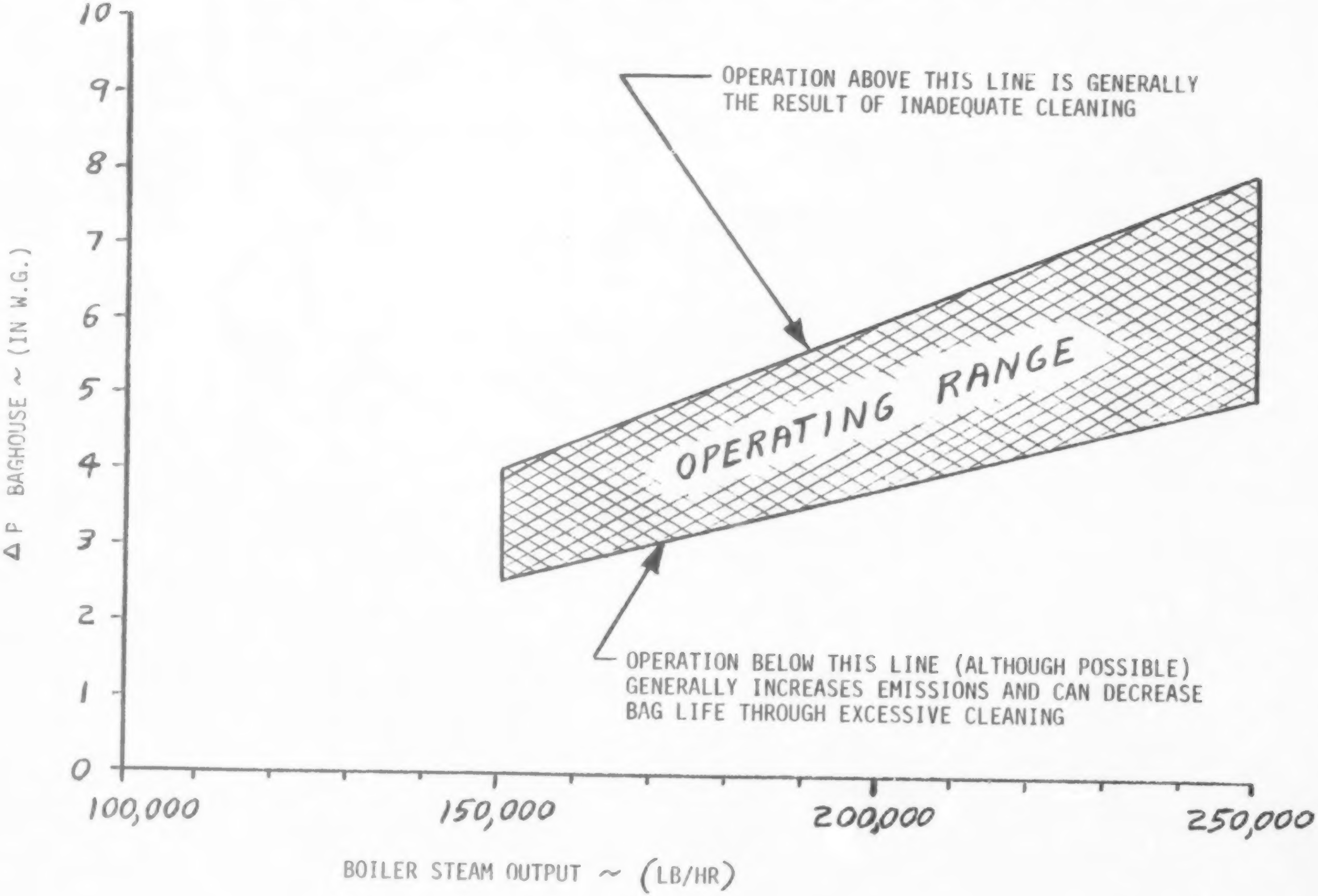


FIGURE 3 BOILER NO. 4 BAGHOUSE ΔP CHARACTERISTIC



OPERATION ABOVE THIS LINE IS GENERALLY THE RESULT OF INADEQUATE CLEANING

OPERATION BELOW THIS LINE (ALTHOUGH POSSIBLE) GENERALLY INCREASES EMISSIONS AND CAN DECREASE BAG LIFE THROUGH EXCESSIVE CLEANING losses at the rated boiler load condition. Operation below the lower line of Figure 3, although possible, generally causes increased emissions and can possibly decrease bag life through excessive cleaning. Operation above the upper line in Figure 3 is not very desirable from a power consumption standpoint. In addition, if the filter cake is built up fairly heavy, a condition develops where bag cleaning can not be accomplished adequately without reducing boiler load.

Several different types of western coal have been used to fire Boiler No. 4. Four of these coals and their basic properties are listed in Figure 4. In general, the low BTU, high moisture coals tend to increase baghouse pressure drop. Also, the higher the ash content in the coal, the higher the baghouse pressure drop. When the high BTU, low ash coals (like Coal C) are burned, there is considerable time when the baghouse is not in a clean mode of operation.

BAG REPLACEMENT INFORMATION

The recorded data on the number of bags replaced per month for each compartment is illustrated in Figure 5 for the time period from February, 1978, through June, 1979. Unfortunately, no data was recorded by operating personnel concerning the bags replaced due to failure prior to February, 1978. Personnel involved in replacing bags during the 14 month period from December 1, 1976, through January, 1978, estimate from memory that somewhere in the range of 200 to 300 bags were replaced during this period due to failure for one cause or another.

Originally, compartment #6 had Cris-O-Flex bags and compartment #7 had Teflon B finish bags, both manufactured by W. W. Criswell. Due to pressure drop considerations, these bags were replaced with Silicon Graphite finish bags in July, 1977, and longer J support hooks were installed in these two compartments. These longer J hooks developed a top of bag total horizontal throw of 3.2 inches during shake instead of the original 1.9 inch shake throw which is still used on compartments #1, #2, #3, #4, #5, and #8. The bags installed in compartments #6 and #7 in July, 1977, were too long and were cuffed over. It is suspected that this cuff slipped, eliminating bag tension. The loss of tension, combined with longer than necessary bag shaking during certain tests, probably caused the high bag failure rate in May and June of 1978.

New bags of the proper length for the longer J hooks were installed in compartments #6 and #7 in August, 1978. To develop comparative data between long and short J hooks, the bags in the adjacent (mirror image) compartments #2 and #3 were replaced at the same time. Since August, 1978, there have been no bag failures in compartments #6, #7, #2, or #3.

FIGURE 4

VARIOUS WESTERN COALS WHICH HAVE BEEN USED

	COAL A	COAL B	COAL C	COAL D
Heating Value (BTU per LB)	8,600	10,700	12,500	11,100
Moisture Content (%)	26	9	7	8
Sulfur Content (%)	.5	.9	.5	.5
Ash Content (%)	9	11	7	10
Ash (Lb Per Million BTU)	10.5	10.3	5.6	9.0
Δ P Baghouse (inches W.G.) (at 250,000 lb/hr steam)	9.0	7.3	5.3	6.0

Figure 5

BAG FAILURE RATE PER MONTH - SINCE FEB. 1978

BOILER NO. 4 BAGHOUSE - START UP DATE DEC. 1, 1976

	1978											1979					
	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR.	MAY	JUNE
COMP. #1			6		3				3							NEW BAGS 5-14-79	
COMP. #2		2					NEW BAGS 8-28-78										
COMP. #3			1		1		NEW BAGS 8-28-78										
COMP. #4	3			4	12				38		4	19		NEW BAGS 3-19-79			
COMP. #5				2					13		9	10			NEW BAGS 4-30-79		
COMP. #6		7			23		NEW BAGS 8-28-78										
COMP #7		6		22	56		NEW BAGS 8-28-78										
COMP #8		26			7				12		7	5	7	NEW BAGS 3-14-79			

NOTES:
1) NO BAG FAILURE RECORDS WERE KEPT PRIOR TO FEB., 1978
2) LONGER J HOOKS WERE INSTALLED IN COMPS. #6 AND #7 IN JULY 1977. THESE COMPARTMENTS STILL HAVE THE LONG J HOOKS.

The original bags in compartments #4 and #8 were replaced in March, 1979, after approximately 26 months of service. The bags in compartment #5 were replaced on April 30, 1979, after approximately 27 months in service.

In summary, it is felt that a major portion of the bag failures were caused over a period of time by a combination of high flue gas flow rates, excessive bag shaking at times, and improper operation of the reverse air fan control damper.

With these items corrected and proper operation in the future, it is felt that it is reasonable to expect between 2 and 3 years of bag life and possibly more.

EMISSION TESTS

Emission tests measuring the amount of particulate in the stack gas were conducted June 7, 8, and 9 of 1977, and the results are presented in Figures 6 and 7. One set of test data (Figure 6) was obtained by the Coors Spectro-Chemical Laboratory (Ref. 1) using EPA Reference Method No. 5. The second set of test data (Figure 7) was gathered on the same days at about the same time by York Research Corporation (Ref. 2) under an EPA contract using a modified form of EPA Reference Method No. 17.

The results tend to vary somewhat between tests #1, #2, and #3 in both data tables. However, the composite average of the three tests compare closely between the Coors Sprectro-Chemical Laboratory data and the EPA-York Research data if only the Grains/SCFD, Grains/ACF, and LB./HR. data is compared. It appears that an unrealistically high BTU input number was used in calculating the lb./million BTU ratio in the EPA-York Research Corporation Report (Ref. 2).

It is of importance to note, however, that all data points were less than the Federal and Colorado limit of 0.1 lb./million BTU.

During these tests the air to cloth ratio was 2.7 when all eight compartments were on line and 3.1 when one compartment was in a clean mode. Baghouse pressure drop outlet plenum to inlet plenum was 9 inches W.G., typically at the 3.1 air to cloth ratio. Coal A, defined earlier, was used during these tests.

A continuous opacity monitor has been installed in the stack flue gas stream (Lear Siegler RM-41). Opacity ranges between 2% and 5% but it is less than 3% most of the time. Generally speaking, there is no visible plume from the stack on this unit and we are pleased that the fabric filter has performed very well.

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FIGURE 6
EMISSION TESTS - BOILER NO. 4
DATA BY COORS SPECTRO-CHEMICAL LABORATORY

(Using EPA Reference Method No. 5)

Particulate Emissions	Test #1 6/7/77	Test #2 6/8/77	Test #3 6/9/77	Average 3 Tests
Grains/SCFD	0.03465	0.01883	0.01085	0.02144
Grains/ACF	0.01654	0.00902	0.00521	0.01025
LB/HR	25.00	14.02	7.90	15.64
LB/Million BTU	0.0714	0.0401	0.0226	0.0447

NOTE: 40 Sample points of 3 minute duration each were taken for each test.

FIGURE 7
EMISSION TESTS - BOILER NO. 4
DATA BY EPA AND YORK RESEARCH CORPORATION

(Using the total of in-stack + out of stack by a modified EPA Reference Method No. 17)

Particulate Emissions	Test #1 6/7/77	Test #2 6/8/77	Test #3 6/9/77	Average 3 Tests
Grains/SCFD	0.01931	0.01774	0.02470	0.0206
Grains/ACF	0.00918	0.00852	0.01178	0.00983
LB/HR	14.21	13.21	20.60	16.01
LB/Million BTU	0.0336	0.0316	0.0428	0.0360

NOTE: 32 Sample points of 4 minute duration each were taken for each test.

FUTURE PLANS - BOILER NO. 5

A new pulverized coal fired boiler with a generating capacity of 450,000 lb./hr. is currently under construction and scheduled for start-up in November or December of 1979. Careful consideration was given to the alternatives of purchasing a reverse air unit, purchasing a shake-deflate unit, designing and building a reverse air unit, and purchasing a low pressure pulse-jet type unit. The low pressure pulse-jet type unit offered by CEA Carter-Day of Minneapolis, Minnesota was selected based on considerations of overall lower initial capital cost and system simplicity and reliability.

The 12 modules for this fabric filter system have been delivered and field installation is progressing on schedule.

Figure 8 lists the significant information concerning this fabric filter system and Boiler No. 5.

REFERENCES

1. Coors Spectro-Chemical Laboratory Report No. 91353. Compliance Tests Report for Adolph Coors Company Power Plant, Boiler No. 4. Coors Spectro-Chemical Laboratory, P.O. Box 500, Golden, Colorado 80401. July 7, 1977.

2. Emission Tests at Adolph Coors Company No. 4 Coal-Fired Steam Generator. Report No. 77-SPP-17. Prepared by York Research Corporation for U.S. Environmental Protection Agency under Contract No. 68-02-1401. Task No. 33. YRC No. 7-8479-33. July 26, 1977.

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FIGURE 8

BOILER NO. 5 BAGHOUSE UNIT - UNDER CONSTRUCTION

A. Baghouse Information

Manufacture: CEA-Carter Day

Model No.: 376RF10 (High Temperature)

Number of Modules: 12 circular configuration

Number of Bags: 376 per module
4512 bags total

Design Flue Gas Flow: 320,000 ACFM at boiler M.C.R.

Total Filter Area: 57,600 Sq. Ft. (4800 Sq. Ft. per module)

Air to Cloth Ratio: 5.5 (with 12 modules)
6.0 (with 11 modules)

Bag Size: Oval pattern 15.3 inch perimeter by 10 feet long

Bag Material: 22 ounce felted "Daytex" (a Carter-Day felted media)

Cleaning Method: Periodic on-line reverse air pulses from a storage tank charged at 7.5 PSIG. Each module has its own self-contained compressor-blower to charge this tank.

System Dampers: Any module can be isolated for maintenance while the boiler and other modules are in service. All modules can be bypassed via two 60 inch diameter poppet bypass valves during start-up or boiler oil firing.

Anticipated Pressure Drop: 3 to 6 inches W.G.

Scheduled Start-Up: November or December, 1979

B. Boiler Information

Manufacture: Combustion Engineering

Type: Model VU-40 tangentially pulverized coal fired with three coal levels being fed by three Raymond RB-613 pulverizers. Unit will be operated balanced draft at a minus 1/2 inch W.G.

Economizer: Unit has a boiler feedwater economizer which will lower the flue gas temperature to less than 360°F.

Steam Rating: 450,000 lb/hr at 825 PSIG and 850°F

Back Up Fuel: No. 2 fuel oil

Steam Use: Steam produced from this and other units at the plant is or will be used for process heat requirements, electrical power generation, and numerous steam turbine mechanical drives.

FABRIC FILTER EXPERIENCE AT WAYNESBORO

BY:

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ABSTRACT

The paper describes a reverse flow fabric filter installed to handle the flue gases from four pulverized coal and oil fired boilers. The unit contains many unique design features which assist with full time operation. Start up was by procedures designed to minimize gas condensation and other undesirable occurrences.

The unit has been on the line for 18 months. Operation has been good with pressure drop varying between 3" and 6" and cleaning frequency varying between 12 hours and continuous. Some few bags have been damaged due to sulfuric acid condensation resulting from maloperation and water leaks. Several operating incidents will be discussed. #6 fuel oil is sometimes burned with the coal.

When the Clean Air Act Admendents were passed in 1970, all Waynesboro boilers were fired with coal. Since No. 6 fuel oil was plentiful and reasonably priced, investment monies necessary to equip Waynesboro to burn oil were authorized. The compliance plan accepted by the State was to be 100% oil fired by the end of 1974. In 1973 the Federal Energy Allocation Act restricted the use of oil as a power generation fuel. A review of the situation considering the quadrupled price of oil and our dependence on it for chemical feed stocks caused us to evaluate available technology to permit burning coal and still meet the Virginia State Implementation Plan of 0.18# particulate/MM BTU input for our plant. Electrostatic precipitators were ruled out due to:

- Modular design not being available.
- Unacceptable roof loading requiring a cold end location.
- The low sulphur content in the coal we use.

The baghouse route was selected and while basic concept designs and project strategy were being developed we evaluated the two alternates - pulse jet and reverse air cleaning. The reverse air cleaning type was selected and authorization to proceed obtained. Rowan Perkins has presented a paper on the considerations used in selecting our baghouse.[1]

The full size Waynesboro installation is shown as a single filter in Slide #1 manifolded to handle gases supplied by four boilers. Each boiler has a bypass directly to the stack. Under normal operation the individual boiler induced draft fans pull the gases from each boiler and discharge them to the baghouse inlet breeching. The booster fans maintain the 2" suction at the filter inlet and overcome the resistance of the filter, discharging gases to the stack breeching. Although we were reluctant to try rapid bypassing of a boiler unnecessarily, circumstances have caused such bypasses and the system has worked very successfully - several times. There were no disturbances of individual boiler controls.

Slide #2 is a "before" picture of the Waynesboro Powerhouse. The left hand stack is handling the coal burning boilers. The baghouse is under construction on the right. Neil Zittere was the Design Project Engineer and deserves a great deal of credit for the nice looking and nice operating unit. Slide #3 is a picture of the completed installation in operation. The same stack is still operating but you can see nothing. This unit was started up September 30, 1977.

The elimination of the smoke is a result of a program which took 3 years to Define, Construct and Start up this baghouse and its auxiliaries.

SPECIFICATIONS

The filter is 50' wide, 100' long and 70' high. The system was designed to handle 340,000 acfm of flue gas to clean the fly ash remaining in the flue gas after individual high efficiency mechanical collectors

Specifications are as follows:

- air to cloth ratio is 2:1 cfm/ft^2 of filter surface with 2 modules out of service.
- operating temperature is normally 340°F with 415°F max.
- 16 modules with 256 bags per module for a total of 4096 bags.
- bags are 8" diameter by 22' long with 5 anit-collapse rings.
- 9.5 oz fiberglass material with a Teflon® B filter fabric finish (Slide #4)
- filter to operate under suction.

The flue gas to be cleaned comes from 4 water tube pulverized coal fired boilers with a total capacity around 600M/hr of steam. The coal we are burning is approximately 15% ash. At rated load this is 66 tons per day. At present steam loads, the new baghouse collects 7 tons/day while the remainder is split between furnace ash and that removed by our mechanical separators.

At Waynesboro we added extra instrumentation to find out more about fabric filter operation. Normal installations have manometers for measuring pressure drop across each module. We have added a pitot tube fixed in the outlet of each module to indicate relative flow. (Slide #5) We wanted to check the assumptions made on module performance as a result of differential pressure only. Already we have seen some indications that previous assumptions are not 100% valid. However, the individual single pitot measurement is not as accurate as desired. Further study will provide better means to analyze fabric filter performance. We are also equipped to test outlet dust loading of each module. All modules are equipped with sight ports to inspect for ash from loose or damaged bags and to observe bag cleaning. (Slide #6)

START-UP SEQUENCE

Having selected the type of baghouse with extreme care and evaluation, we recognized that our goal consisted of 3 major items.

- A good smooth start up.
- Continuous operation firing coal, oil or a combination.
- Low maintenance and long bag life.

We spent considerable time in the development of a start up procedure under the guidance of Rowan Perkins[2], Niel Zittere and both vendors, Western Precipitation (Baghouse) and Minardi Southern (bags). Preliminary check out of individual pieces of equipment and systems took about 2 weeks. (See Appendix 1 for problems.)

START-UP WEEK

The first day was a final meeting within Du Pont among Operations, Engineering Design and Power specialist group. This included a step by step review of our start up sequence and final modifications to adjust for the actual operating configuration of the Powerhouse, physical verification of actual conditions throughout the system and final adjustments of controls.

The second day finished the verification of baghouse conditions and included a meeting with the baghouse and bag vendors to review their concerns. One of them was the looseness of the bags which indicated a need to retension the bags in the entire unit. All items were corrected and by the end of the 3rd day we were ready to commit to start up on the 4th day and ready to work long hours.

START-UP

Our philosophy was that this would be the only start-up as the baghouse was scheduled to be on line continuously. Subsequent operations were to consist of cutting modules in and out of service for maintenance. Our start-up procedure was very detailed and is contained in Appendix 2.

Briefly, we assumed four boilers would be operating through their by-passes with a total steam load of 300,000 lbs/hr equivalent to flue gas flow of 170,000 acfm (actual feet per minute). While this requires only 8 modules we planned to use 12.

We selected modules 6 and 8 to remain down. The selection was dictated as 2 and 4 were unbagged and we wanted to minimize outside wall exposure.

We did not precoat the bags, but in order to minimize flue gas condensation on the bags; the baghouse and breeching temperatures were brought up using gases from one operating boiler through the 2 empty (unbagged) modules number 2 and 4. All other modules were closed off.

Modules with bags were then brought on line using flue gas at normal temperatures and with fly ash having normal characteristics. Boiler loads and baghouse parameters were used as criteria for selecting the number of modules required as each additional boiler was put into the system. We continue to use these parameters.

Start-up was smoothly accomplished (with no long hours) during the week of 9/26/77, three months ahead of schedule and yielded a savings of $120M by burning 100% coal instead of 80% during 4Q77. Performance was and is extremely satisfactory with no plume. Optical instrumentation monitoring the stack reads 2% when the baghouse is used as designed.

OPERATIONS

- This was the smoothest start-up Western Precipitation had witnessed due to advance preparations which included:

- one year studying start-up and operation of other installations
- 2 man months writing start-up and operating procedures involving a total of 6 people at various times.
- Construction follow-up by operating supervisors and engineers with documentation of tests and checks.

- We eliminated changes in the booster fan loading due to reverse-air cycling by taking the reverse air suction off after the booster fan discharge. Now the cleaning cycle does not disturb booster fans or boilers and controls operate satisfactorily.
- Mechanically we have had by-pass damper problems associated with both design and construction. Lack of rigidity in design and some welding not done during fabrication.
- We have proven the booster fan control concept. Boilers can be by-passed without upsetting the boilers. This is a first in control design. No changes were made in boiler controls.
- A performance test was run 8/29/78. The delay was required to correct the leakage between the thimbles and the tube sheet at the entrance to bags. Slide #7 and #8 show the sealing compound used to accomplish sealing. The average emission was 0.0036 gr/A ft^3, which is 0.011 #/MM BTU and well below the State required 0.18#/MM BTU and less than .01 grains per actual ft^3 air, our contractor guarantee.
- Normal ΔP is maintained between 3" and 6" across the baghouse or 2" to 3" across the bags themselves. Reverse-air cleaning is varied to accomplish this and varies from once every 12 hours to continuous, depending on boiler loads and ash content.
- Bags have been successful and operate well with an estimated average life of 5 plus years. One module is equipped with bags of woven Teflon® fibers as a test for Company fabrics.
- Tests also indicate that there is the same relative particulate size distribution on inlet and outlet. (Electrostatic units do not filter the smaller particles.)
- We are selling fly ash from the baghouse for light-weight concrete products.
- We had an increase of ΔP across the baghouse to 6" which required putting the 13th module in operation. Our plan is to individually clean the bags in each module that has been on line. Cleaning will be done by removing modules from service but leaving the bags in place while they are air blown from top to bottom.

- The filter is automatically bypassed if inlet gas temperature exceeds 450°F, or if inlet suction drops below 0.5 in. An automatic atmospheric damper prevents implosion of the filter house in case of sudden bypass.

- Individual boilers are bypassed if furnace draft remains above 0.1" for 10 seconds.

MAINTENANCE

There have been a total of 35 bags replaced since January 1, 1978. Twenty-nine (29) of the defective bags have been in either Module No. 10 or No. 12. These modules were included in the initial start-up but were removed from service after one or two weeks of service in an attempt to raise the gas temperature on the baghouse. They were left closed and it appears that there was flue gas leaking into these modules that set up an acid condition, loss of bag material strength due to acid attack. Procedure for removing modules has since been changed to having doors open on idle modules, thereby maintaining a slight in-flow of air through dampers so as to prevent leakage of flue gas into the idle units. There have been two bags replaced in No. 1 Module which has the "Teflon" bags and these bags appeared to have been installed improperly. One bag has been replaced in No. 16 Module which was caused by a bent thimble that may have torn the bag on initial installation. Recently, three bags had to be replaced in Module No. 9 due to small holes. We feel this must have been unnoted installation damage as no other causes are apparent.

Module entry has been a question in some minds with the reverse air type baghouse. The modules are removed from service by closing the inlet and outlet dampers. Installing a fan in the valve access door located on top of the module and opening the lower access door provides a purging flow of air. Heat flow from adjacent modules is reduced by insulation between modules. After a few hours of module cooling with purge fan in operation, bag replacement can be accomplished by the mechanic in cool air. Dust masks are worn because there is some dust on the clean side.

Safety is maintained by following these safety steps:

- Isolating the module, locking it out, obtaining an air analysis inside the module.

- Defective bags must be located and then dust cleaned from floor to prevent entrainment when returned to service.

- Bag replacement requires 3 mechanics: one top, one bottom and a standby exterior to the module.

Our major maintenance efforts have been associated with the fly ash removal system including the bag filter connected to the ash removal system. Most of the problems are the results of the ash being damp and causing line and equipment pluggage. These problems seem to have been greatly reduced due to enclosing the equipment on top of ash silo and insulating the electrically traced module hopper discharge valves.

This brings us up-to-date. We are continuing to learn the fine points of operating and maintaining our $6MM vacuum cleaner and anticipate finding out more of its capabilities as time goes on.

GENERAL EXPERIENCES

1. Tests were run of mixed coal and #6 fuel oil firing in early 1977 using a reverse-air type pilot baghouse. Using flue gas from coal and #6 oil at a 50-50 ratio, tests indicated that the pressure drop build up while filtering and regain after cleaning was better than straight coal firing. No adverse effects were noted even at low gas gemperatures. We have passed the flue gas from our large boilers at various ratios of coal and both #2 and #6 flue gas oil firing up to 50-50 ratio through the baghouse without seeing any detrimental effect on filtering pressure drop or regain after cleaning. No bag failures or "smearing" have resulted.

2. There is still some water leakage in and around the valve boxes. We have located a sealing material which expands to fill a void and plan to evaluate its ability to seal the leaking joints.

This baghouse is now an integral piece of operating equipment that will stay efficient. We have 3 other RA fabric filters in the Company which are giving comparably good performance.

APPENDIX 1

CHECK OUT - PROBLEMS

This phase was continuous through out the construction and even then we found problems at the end. The main problems were:

- The isolation of individual cells to assure good filtering, bag cleaning during continuous operation, and satisfactory isolation for maintenance. This involved checking of actual clearance between each valve disk and its elastomeric seat over the entire mating surface. In-place grinding and minute final adjustments took days.

- Bag installation and tension, 38#/bag, to assure support that permits normal ballooning and collapsing during operation, Since the bags had been installed several months previous to start up, retensioning was required throughout the unit.

- Control sequencing - including the coordination of all the automatic valves from the panel board used in reverse-air cleaning as well as the controls for the booster fans.

- Ash removal system was designed to handle hot, dry, free-flowing ash and did not operate well initially. Line and separation gate pluggage was severe until we corrected deficiencies such as leaking gates and insufficient insulation. Initial startup residue had to be cleaned off hopper slope sheets. Knife edge gates were used finally.

- Internal leakage - This last problem was solved 9 months after start-up. It involved the loss of the seal where the lower bag thimble goes through the tube sheet. With our assistance the vendor sealed the leak between thimble and tube sheet with a hardening liquid called Pelmor®. This is a liquid suspension of Vitron® elastomeric material.

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APPENDIX 2

BAGHOUSE START-UP DETAILS

POWERHOUSE OPERATING CONDITIONS

- Boilers 2, 3 and 4 - 200,000 stm/hr total.
- Boiler 1 - 100,000 lb stm/hr.

START-UP PROCEDURES

1. Check Modules 1, 3, 5, 6, 9, 19, 11, 12, 13, 14, 15 and to to assure that the inlet and outlet isolation dampers are closed. Flapper valve box should be open to the outlet, closed to reverse-flow duct. Inlet and outlet dampers to Modules 6 and 8 are to be locked shut. No booster fan on standby.

2. Inlet and outlet isolation dampers of Modules 2 and 4 should be wide open. Flapper valve in the module valve box should be open to the outlet and closed to the reverse-flow duct.

3. Open inlet and outlet isolation dampers of south and middle (Nos. 3 and 2) booster fans. Close inlet control dampers on the control panel. (They will be automatically closed when the fans are down, put will open rapidly when the fan starts.)

4. Set the No. 1 bypass damper to the location (open) to give the desired start-up condition.

5. Set atmospheric vacuum relief valve open.

6. Start the south (No. 3) booster fan. With the baghouse suction control (fan inlet damper control) on manual and closed, start the fan. Adjust vacuum relief valve and fan inlet damper to obtain 2" suction at the baghouse inlet.

7. Place No. 1 Boiler on manual control. Assure personnel are out of #4 Boiler while damper is switched.

8. Gradually close the No. 1 Boiler bypass manually (highest temperature). (Gas will flow through Modules 2 and 4, which have no bags, to permit full warm-up of the inlet and outlet breeching.) Gradually close vacuum relief valve to maintain 2" suction. Open booster fan inlet damper as necessary.

9. Carefully observe No. 1 furnace suction and baghouse inlet suction as the bypass transfer is gradually completed. Adjust baghouse suction control (booster fan inlet dampers) and vacuum relief valve to maintain -2".

10. Close vacuum relief valve if not already closed.

11. When fan inlet control damper is maintaining 2" suction at the baghouse inlet, place suction control on automatic. Observe its operation to assure even control. Adjust control sensitivity as necessary. By this time the bypass damper on No. 1 should be closed.

12. Carefully observe the warm-up and expansion of the breeching and Modules 2 and 4. Reference indicators have been installed at many points. Particular attention should be paid to the compression of expansion joints. Note the temperature rise at the baghouse outlet using the boiler control board temperature recorder.

13. When (1) the booster fan controls are operating properly to maintain 2" suction at the baghouse inlet, (2) the proper furnace suction is maintained in the No. 1 Boiler, and (3) the baghouse outlet temperature has leveled off (should be 10-25°F below inlet), the filtering modules can be opened.

14. Gradually open the inlet and outlet isolation dampers to Modules 3, 5 and 7. (Most of flow will still be through Modules 2 and 4).

15. Gradually close the outlet isolation damper to Module 2. Operate this slowly to give the suction control time to compensate for the increased pressure drop of the bags.

16. Repeat Step 15 closing off Module 4 outlet isolation damper.

17. Close the inlet isolation valves on Modules 2 and 4. (Maintenance: Open the access manhole to the valve box and install the purge air fans in Modules 2 and 4. Open the lower aisle access door and fully purge the modules. After they have been purged for several hours, seal the inlet and outlet isolation dampers and otherwise secure the units.)

18. For experience by the operator and to determine the effects of different operations, several items can be tried.

    a. Gradually open the bypass to transfer gases directly to the stack in the reverse of Steps 8 and 9 (operating so that baghouse inlet suction does not exceed 12"). It will be necessary to open the vacuum relief valve to keep vacuum in range.

b. Reactivate the baghouse by following Steps 8 and 9.

After approval by W. R. Denney (Powerhouse Supervisor)

c. Trip the bypass to place the gases to the stack to determine all responses. Be careful to observe all furnace fluctuations in No. 1 Boiler and be prepared to kill the fires if necessary. Relighting and retrials can be made to determine responses and best procedures.

d. Close bypass gradually without closing vacuum breaker to check booster fan pick up.

When satisfied that the booster fan and all controls operate satisfactorily, proceed to to add more boilers to the baghouse.

19. Open the inlet and outlet dampers to Module 9 and 10. This may cause a change in baghouse differential (Δ P), so be sure the suction control damper is holding proper suction. (Check the flow indicators. Modules 3, 5 and 7 will probably be less flow than Modules 9 and 10. If there is more than a 2:1 difference in flow, open the inlet and outlet isolation valve to Module 11.)

20. Observe the warm-up of the additional modules. Observe both the expansion clearances and the temperature increase.

21. Gradually close the bypass damper of Boiler No. 3 while watching the baghouse suction (maintain -2") and the furnace suction. (If long delay, reverse Step 19.)

22. When the bypass damper is closed, observe the temperature rise of the baghouse outlet. (It should have dropped when the new modules were added but should return to normal, 10-20°F lower than the inlet temperature.) Continue to observe the flow indicators to Modules 3, 5, 7, 9 and 10. They should tend to equalize.

23. Be sure the inlet control damper and automatic/manual control station on the middle (No. 2) booster fan are closed. (The inlet and outlet isolation slide gates were opened in Step 3).

24. Start the No. 2 booster fan, observing the effect on the suction of the No. 3 fan. Inlet dampers may close somewhat to maintain 2" suction in the baghouse inlet.

25. Gradually open the inlet control damper on the No. 2 fan. The automatic control on the No. 3 fan should gradually close to maintain suction at 2".

26. When the control positions for both fans are the same, place No. 2 fan on automatic and observe automatic control of the baghouse suction.

27. By this time the differential of the operating modules may have increased to the point where cleaning is desirable, say 1-2". If not, continue to Step 27.

    a. If so, add another module (11 or 12) per Step 19.

    b. Adjust the timers and controls to clean Modules 3, 5, 7, 9, 10 and 11 for settling periods of 40 sec. and one cleaning period of 40 sec. Do not clean modules with lower $\triangle$P.

    c. Start one reverse-flow fan. (The inlet should be throttled to use a minimum flow and pressure. Several trials may be necessary. The pressure and flow should be no more than necessary to effect the desired cleaning.)

    d. Operate the fly ash removal system on hoppers of cleaned modules. Check ash suction to be sure all are emptied.

Conduct step * only on request of W. R. Denney (Powerhouse Supervisor).

* At this time, various other items can be tried - switching between fans (removing the No. 2 booster fan from service and cutting it back in) and both gradual and sudden bypass damper operation. With both fans in operation, proceed.

28. Open the inlet and outlet dampers of the next two modules (11 and 12, or 12 and 13). Closely observe the baghouse suction controls to assure maintenance of the 2" baghouse suction.

29. Gradually close the bypass damper of boiler No. 2. Check bypass damper operation.

30. When the bypass damper is closed, observe the baghouse outlet temperature. (It should have dropped when the new modules were added but should return to normal 10-20°F lower than the inlet temperature.)

Continue to add modules

31. Open the inlet and outlet dampers to the next two modules (12 and 13 or 13 and 14). Observe that the controls to the fans maintain the 2" suction.

32. Gradually close the bypass damper of No. 1 Boiler. Observe the baghouse suction controls. Check bypass damper operation and travel.

33. When the bypass damper is closed, observe the baghouse outlet temperature. (It will have dropped when the additional modules were opened but should level out 10-20°F below the inlet temperature.)

34. Open the inlet and outlet dampers to the remaining modules (14 through 16). Observe the suction controls.

After baghouse is operating successfully with all boilers:

35. Shut down #4 Boiler.

36. Observe the baghouse outlet temperature. It should level out 10-20°F lower than the inlet.

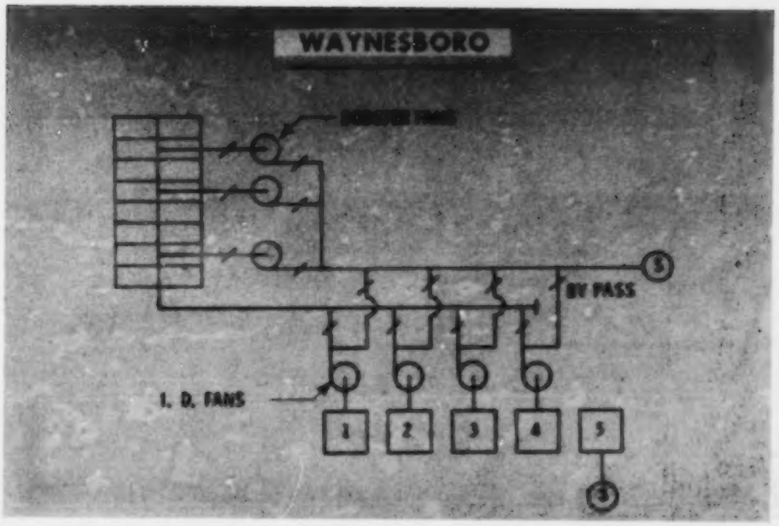
37. Set the cleaning for all modules at one cycle with 40 sec. settle and 40 sec. clean. Operate single cycle at 40 sec. to maintain P between 3" and 4".

38. Operate fly ash hopper cleaning system. Check for proper pulling of all hopper.

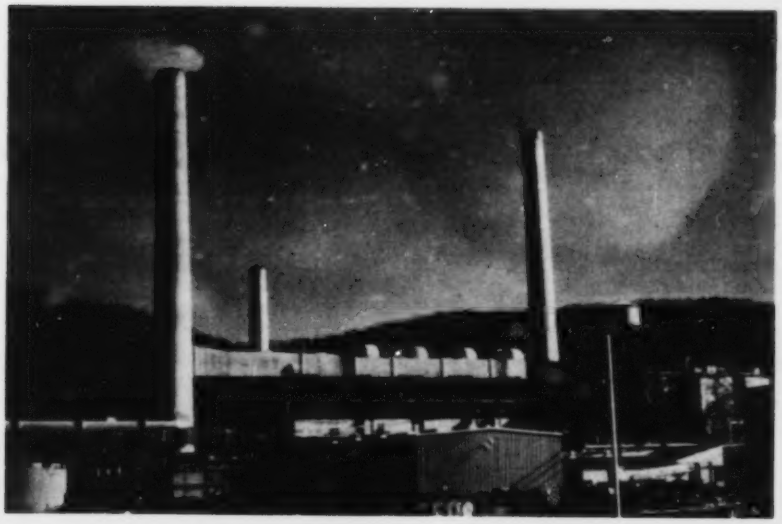
REFERENCES

[1] "Case for Fabric Filters or Boilers" by R. P. Perkins. Presented at Massachusetts-APCP, Philadelphia 1976.

[2] "Consideration in the Start-Up of Baghouse in Coal Fired Boilers" by R. P. Perkins, presented at Second Annual Filter Fabric Alternatives Conference, Denver 1977.

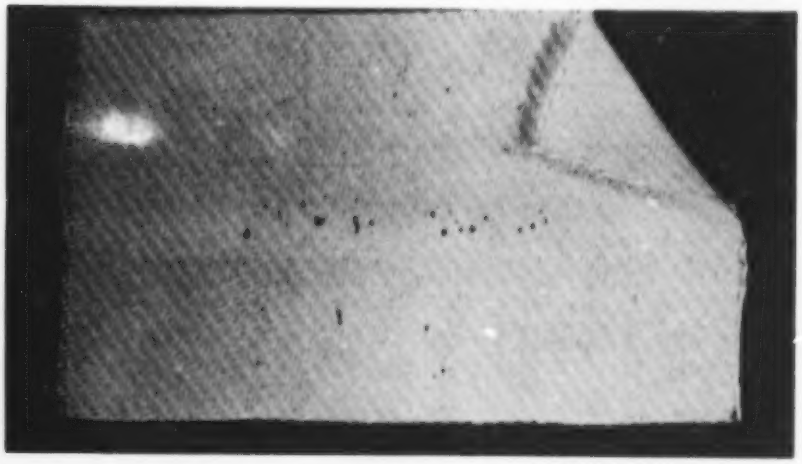


"SLIDE 1"   WAYNESBORO BAG FILTER SCHEMATIC



"SLIDE 2"   WAYNESBORO POWER COMPLEX BEFORE

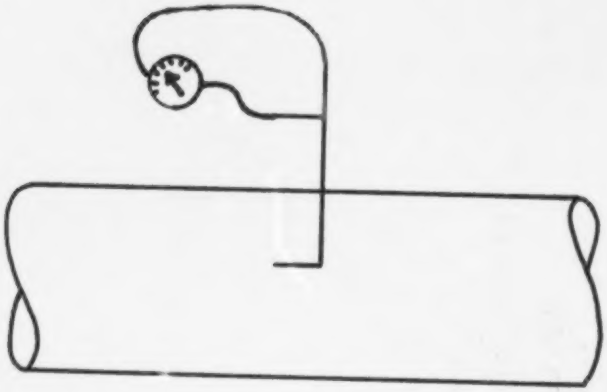
"SLIDE 3" WAYNESBORO POWER COMPLEX AFTER



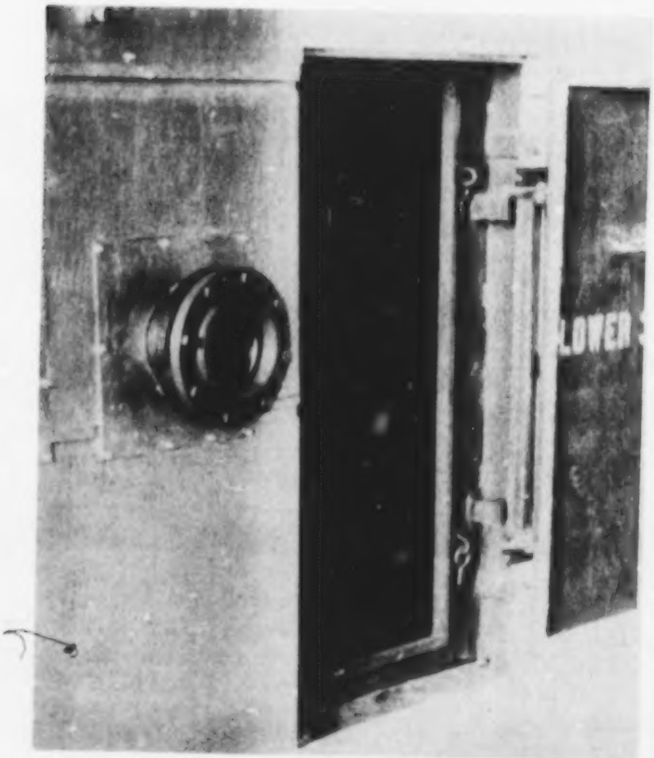
FIBERGLASS WITH TEFLON B® COATING

"SLIDE 4" BAG MATERIAL SAMPLE

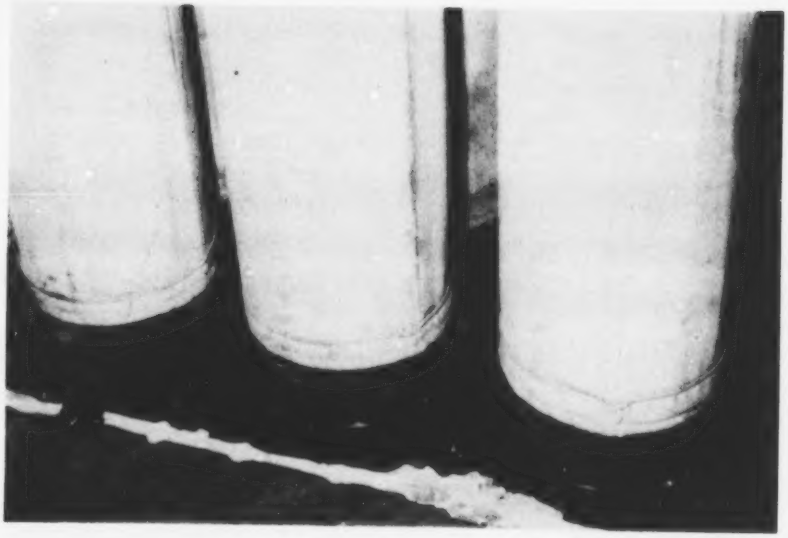
MODULE PITOT TUBES



"SLIDE 5" ADDITIONAL INSTRUMENTATION



"SLIDE 6" MODULE SIGHTGLASS



"SLIDE 7" SEALING WITH PELMOR®

"SLIDE 8" SEALING WITH PELMOR®

A NEW TECHNIQUE FOR DRY REMOVAL OF SO_2

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August 1979

ABSTRACT

Experimental studies are reported on a technique for SO_x flue gas control using a dry limestone sorbent and humidification control of the flue gas. Kinetic studies of this "modified dry" limestone process (MDLP) show reaction rates equivalent to high temperature fluid bed processes. SO_x removal efficiency is shown to increase as the water saturation temperature of the "conditioned" gas increases. At a saturation temperature of 150°F one can obtain >90% SO_x removal from a flue gas stream containing 1600 ppm SO_2. Results of economic analysis based on both a moving bed and a counterflow design are presented.

A NEW TECHNIQUE FOR DRY REMOVAL OF SO_2

INTRODUCTION

Lime/limestone scrubbing is presently considered the best available control technology (BACT) for flue gas desulfurization, but most wet methods have characteristic problems of high cost and low reliability. Dry alkali injection has been proposed as a potentially viable alternative to wet scrubbing for flue gas desulfurization (FGD). The concept of dry alkali injection is simple and involves two basic operations: 1) injection of reactant, and 2) removal of solid reaction products. The reactant may be injected as a dry powder, a solution of a soluble alkali, or possibly as a slurry of a relatively insoluble alkaline earth compound. If introduced as a solution or slurry, the liquid evaporates almost immediately and leaves a suspension of finely-divided solids in the gas phase, which is very similar to that created by the dry injection technique. Subsequent reaction of the suspended solid particles with sulfur dioxide produces solid sulfite and sulfate particles that are admixed with fly ash and unreacted alkali. Removal of these dry solids is effected by a filter (moving-bed/baghouse) or an electrostatic precipitator.

Independent studies (Dickerman et al., 1978)[1] have demonstrated that dry sodium compounds, such as soda ash, trona, or nahcolite, are the preferred reactant(s) for this mode of FGD because of their high chemical reactivity. Results of tests using lignite as a fuel show that sodium salts can absorb approximately 80 percent of the sulfur dioxide from a gas wherein the solids have a short resident time (~3 sec.). Product solids are then removed in an electrostatic precipitator. If these solids are removed in a bag filter, however, additional contact time between the gas and solids is provided and can result in higher removal efficiencies. The combination of the two processes (dry injection and filtration) has been used to provide up to 99 percent removal for SO_2 (Dustin, 1977).[2] Use of powdered lime/limestone in this mode of treatment normally results in ineffective removal of SO_2, i.e., <50 percent (Bechtel Corp., 1976).[3]

By-products from reaction with sodium salts consist of sulfur-bearing particles that are water soluble and can result in contamination of ground water unless special precautions are taken. One way to avoid water contamination is to treat the sulfur-bearing sodium particles with a lime/limestone slurry. This converts the soluble sulfur compounds to relatively insoluble calcium sulfate (gypsum), thus producing a solution of sodium salts which is available for recycle. This combined treatment increases process costs. Further development of this dry method for FGD, however, could possibly result in a decrease in overall processing costs and may improve equipment reliability when compared to existing BACT.

Studies conducted at the Morgantown Energy Technology Center (METC) indicate that a new approach, using water vapor to "condition" the flue gas, may be effective in removing SO_2 from a cooled gas stream. The patented technique (Shale and Cross, 1976)[4] involves adding water vapor to hot flue gas (300°F) to increase the saturation temperature of the gas above a critical minimum and then cooling the mixture to a predetermined temperature near the adjusted dew point. Under the conditions studied, it has been shown that greater than 90 percent of the SO_2 can be removed using small pellets (up to 1/2-inch) of crushed limestone in a dry bed. The process is called the modified dry limestone process, or MDLP. Through direct use of limestone, a dry, relatively inert sulfur product (gypsum) can be produced without the need for secondary processing of soluble salt solutions. This process has the potential of providing several economic benefits.

EXPERIMENTAL PROCEDURES

Both laboratory scale and bulk evaluation studies have been conducted on MDLP. The laboratory studies were performed using a Mettler DTA-TGA instrument in which kinetic parameters were obtained by observing the change in weight of limestone as a function of time. The apparatus and experimental procedures have been described in an earlier publication (Nesbitt et.al, 1978).[5] The gas stream consisted of 2.5-7.0 percent SO_2, 2.0 percent O_2, and the balance nitrogen. Limestone pellets ranged in weight from 590 mg. to 810 mg. The porosity and surface area of the pellets were monitored and held constant such that observed changes were the result of a chemical interaction, not changes in physical properties. The stream humidity was determined by a wet bulb thermometer and held at the saturation level. Chemical analyses of the solid product was performed by IR, SEM, X-ray flourescence, and ESCA. All analyses were consistent in that 1) calcium sulfate was the major product, and 2) reaction occurred on the pellet surface.

Bulk absorption studies were performed on limestone beds 1-inch diameter x 9- inch deep and 1/2-inch diameter x 4-inch deep, using 1/16 x 1/2-inch pellets. Gas flow rates were controlled between 1 and 3 scfh and were monitored by a gas flowmeter. The pressure drop across the beds varied between two inches of water at the beginning and up to eight inches of water at the end of individual tests. Pressure loss increased because of water deposition on the limestone and the physical particle enlargement resulting from chemical reaction. For all studies the gas mixture was 14 percent CO_2, 4 percent O_2, 0.15 to 0.3 percent SO_2 and the balance N_2. Analysis of the SO_2 removal was determined by commercial gas detector tubes. The tubes were sensitive to water, and the reliability was ± 25 percent of the indicated value. Any SO_2 level below 1 ppm was below the detection limit of the detector.

The bulk investigative tests for this system were conducted in equipment depicted in Figure 1. Simulated flue gas containing up to 3000 ppm sulfur dioxide flowed at a controlled rate through a heater, a heated saturator, and a fixed bed of selectively-sized limestone and was exhausted into a hood. In the experimental program, the gas flow rate, temperature, moisture content, and sulfur dioxide concentration were controlled as process variables. Two limestones and two dolomites of variable particle (lump) size were tested in beds of different diameters and depths to allow for a range in space velocity.

After having established steady state thermal conditions using a selected flow rate of dry gas through the system, a controlled flow rate of water was added continually to the saturator to establish a controlled level of moisture in the "conditioned" gas for each absorption test. Heat added to the saturator insured complete evaporation of all water. The dry gas was heated to 280°F and passed through the saturator prior to entry into the bed of crushed stone. The gas cooled during saturation and flowed through the limestone bed at a temperature of 150° to 160°F and a space velocity of 500 vol/vol/hr.

RESULTS AND DISCUSSION

Thermogravimetric studies on single limestone pellets indicate that SO[illegible] removal efficiencies would be a maximum for a saturated stream temperature of 110-120°F. This can be correlated to the sorption of SO_2 in H_2O as a function of temperature. The sorption of SO_2 in H_2O has been shown to decrease rapidly as the temperature increases. In addition, thermogravimetric studies show no observable weight gain in the temperature range of interest unless water is present. Therefore, it is fortuitus that the optimum conditions for MDLP coincide with actual gas stream conditions.

A representative weight gain curve for water and SO_2 absorption is shown in Figure 2. Kinetic parameters were obtained using the initial rate method. For this study the following stoichiometric equation was assumed for the rate controlling step:

$$a_rA_r\text{(gas)} + s_rS_r\text{ (solid)} \rightarrow a_pA_p\text{(gas)} + s_pS_p\text{ (solid)} \qquad (1)$$

where a and s are the stoichiometric coefficients for gases and solids, and r and p represent reactant and product. It was assumed that both diffusional and mass transfer resistance were negligible such that the initial reaction rate can be represented as:

$$R_o = a_r\, k_s\, C_{s_o}\, C^n_{a_o} \qquad (2)$$

where R_o is the initial molar rate of reaction of the gas per unit surface area of the solid, k_s is the rate constant per unit area, C_{s_o} is the initial molar concentration of the solid, C_{a_o} is the molar concentration of the gas and n is the reaction order with respect to the gas.

It can be shown that the initial reaction rate can be calculated from the weight gain curve by using the following equation (Westmoreland, 1977)[6]

$$R_o = \frac{(a_r/s_r)\ (dw/dt)_o}{m_o\alpha_o \left[M_r + (a_p/a_r)M_p\right]} \tag{3}$$

where $(dw/dt)_o$ is the initial slope, m_o is the initial mass of the solid reactant, α_o is the specific surface area of the solid and M_p and M_r are molecular weights of the solid product and reactant.

The reaction rate, as determined by equation (3), is used to determine the order of reaction with respect to the concentration of the reactant gas and the reaction rate constant as specified in equation (2). The reaction was found to be first order in SO_2 concentration and to obey the classical Arrhenius relationship

$$k_s = A \exp(-E_a/RT) \tag{4}$$

where A is the Arrhenius factor, E_a is the activation energy, R is the gas law constant and T is the absolute temperature. Thus, by plotting ln k_s versus 1/T it is possible to determine both A and E_a.

The calculated intrinsic rate of reaction (R_o) and the initial rate of change $(dw/dt)_o$ are given in Table I. From these data the intrinsic rate constant can be calculated using the initial limestone concentration (2.7×10^{-2} moles/cm^3) and the water concentration at the gas stream temperature. The intrinsic rate constants evaluated by equation (2) with n = 1 were found to obey the classical Arrhenius relationship under the observed conditions where mass transfer resistance was negligible.

To obtain the reaction order with respect to the concentration of sulfur dioxide, experiments were performed in which the SO_2 concentration was varied from 2.5 to 7%. A plot of the initial rate of weight gain of SO_2 concentration at different temperatures is shown in Figure 3. The linear dependence indicates that the reaction is first order in SO_2 concentration.

A mechanism consistant with the experimental kinetic parameters is as follows:

$$SO_2 + H_2O(ad) \rightleftarrows [H_2SO_3] \rightleftarrows H^+ + HSO_3^- \rightleftarrows 2H^+ + SO_3^=$$

$$HSO_3^- + \tfrac{1}{2}O_2 \rightleftarrows HSO_4^-$$

$$CaCO_3 + HSO_4^- \rightleftarrows CaSO_4 + HCO_3^-$$

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2$$

This mechanism involves an acid-base reaction in which sulfur dioxide is dissolved in an adsorbed water layer. The pH conditions in the stream favors the formation of HSO_3^- and are unfavorable for $SO_3^=$, (Schroeder, 1966)[7], (Roberts, 1979)[8]. Therefore, HSO_3^- is considered the dominate species. It is proposed that the HSO_3^- is oxidized to HSO_4^- by dissolved oxygen present in the adsorbed water. This reaction has been shown to be governed by a free radical mechanism and thus occurs rapidly in solution (Schroeder, 1966)[7]. Small impurities of iron and/or copper present in the limestone have also been shown to catalyze this oxidation (Rand, 1965)[9]. The calcium carbonate subsequently reacts with HSO_4^- to form calcium sulfate and bicarbonate ion. The bicarbonate ion reacts with a proton to form CO_2 and water. This mechanism predicts first order kinetics which has been verified experimentally. The product proposed by this mechanism is $CaSO_4$ which has been verified experimentally by IR and ESCA analysis.

For practical considerations it is interesting to compare the kinetic parameters obtained for the modified dry limestone process with the kinetic parameters obtained in the reaction of calcined limestone with SO_2 (Borgwardt, 1970)[10]. As seen in Table II, the activation energies and rate constants are very similar for the two processes. This similarity is fortuitous since the processes occur at greatly different temperatures and the Arrhenius plots are not continuous. However, since the calcined limestone process is economically viable with other techniques, it seems reasonable that MDLP may also be economically viable with other FGD processes.

Bulk studies were performed using conditions similar to those used for the thermogravimetric studies. The effect of saturation temperature on SO_2 removal efficiency is shown in Figure 4. At a space velocity of 500 v/v/hr, an SO_2 concentration of 1600 ppm, a gas temperature of 150°F, and a saturation temperature of 100°F the SO_2 removal efficiency is $\gtrsim$90% for approximately 30 min. and then drops off rapidly with an increase in exposure time. These conditions simulate a stack gas from a conventional coal-fired combustion source burning a 2% sulfur coal and having an exit gas temperature of 150°F. At the higher removal efficiencies the uncertainty in data is considered to be ±5%. As the saturation temperature increases from 100°F to 150°F the maximum removal efficiency is maintained for longer periods of time. Note on curve 2 that after ~2.5 hours, the moisture content of the gas was increased from a level corresponding to a saturation temperature of 110°F to that of 120°F. The subsequent increase in SO_2 removal efficiency is consistent with the overall variation of removal efficiency with moisture content. At a saturation temperature of 150°F a removal efficiency of $\geq$90% was maintained for at least 3.5 hours using a bed of Greer limestone. Tests with other limestones[11] and dolomites[12] show a similar high level of induced chemical activity upon additions of water vapor to the simulated gas stream. The effects of moisture on increasing the SO_2 removal efficiency have also been observed by workers at Battelle (Rosenberg, 1979)[13].

Experiments at higher space velocities (4,000 v/v/hr) have shown that SO_2 removal efficiencies of >90% can be achieved when the gas is at complete saturation, that is, the water vapor saturation temperature is no more than 30°F below the actual gas temperature as it flows through the fixed bed. For these studies the SO_2 concentration in the test gas was 1400 ppm.

Examination of the limestone at the completion of each test showed that the pellets were covered with a relatively thick, soft shell of reaction products. After partial drying of the pellets the product layer could be removed by mild agitation leaving the harder unreacted core of limestone. Analysis of the initial limestone reaction product and the unreacted core are given in Table III. From these results it is apparent that the shell is composed of calcium sulfate plus some unreacted calcium carbonate. Earlier reports (Shale and Cross, 1976)[4] estimated that ~90% of the limestone was utilized in the reaction. However, a more recent reevaluation of the original data suggest that the actual utilization of the limestone is somewhat lower.

A preliminary analysis by the Cost Evaluation Group (1971)[14] of the U.S. Bureau of Mines, using only the data obtained from the bulk studies, indicated that capital and operating costs for MDLP could be as much as 40 percent less than corresponding costs for removal of SO_2 by lime/limestone wet scrubbing systems when a cross-flow moving-bed concept is utilized for the dry absorber. The conceptual design used for this study is shown in Figure 5. A more recent cost analysis has been conducted by TRW (Rao, 1978)[15] which is based on both the bulk studies and the thermogravimetric studies. This latter study, however, uses a concept based upon a counterflow moving-bed which characteristically consumes an excess of energy in pressure loss through the absorber. This study shows capital and operating costs for MDLP in excess of those for lime/limestone scrubbing. The use of dry sorbents and fabric filtration in FGD systems has been evaluated in a report by TRW for EPA (Lutz et. al, 1979)[16]. The capital cost for a dry solvent system utilizing nahcolite was found to be approximately 40% of that for a lime/limestone scrubber system while the operating costs were estimated to be approximately equal. Adaptations of MDLP to a dry injection technique might offer similarly induced capital costs.

CONCLUSIONS

Kinetic studies indicate that limestone is an effective sorbent for SO_2 in moisture laden flue gas streams. Rate data indicate that the reaction process is first order in SO_2 concentration and is reaction rate limited. The products from this reaction are gaseous CO_2 and solid calcium sulfate. The rate of SO_2 removed by MDLP is comparable to the higher temperature fluid bed processes and unlike the low temperature lime/limestone scrubbers, MDLP produces a solid waste product. It is also evident from the experimental studies that the duration of enhanced removal efficiency increases as the water saturation temperature of the "conditioned" gas approaches the actual gas temperature of 150°F. At substantially complete saturation, removal efficiencies of ~90% are achieved over an extended period of time.

Whereas the saturation temperature of combustion gas from coal is about 95° to 100°F (depending on the age of the coal), combustion gas from oil firing is saturated at about 110°F, while the product from gas firing is saturated at about 130°F. The high moisture content of combustion gases from a natural gas-fired source would appear to make this gas ideally suited to cleanup of sulfur dioxide by dry limestone, without modification, as indicated by the data given previously in Figure 4. The saturation temperature of gases from oil- and coal-fired sources, however, is below the established critical minimum (120°F), so the dew point of these gases must be adjusted to a higher level for effective application of this sorption technique. Through addition of adequate moisture and through adequate control of temperature, as specified for MDLP, a properly "conditioned" gas can in principle be produced from any fuel, thus yielding the maximum removal efficiency for sulfur dioxide.

Preliminary economic evaluations have been made on the modified dry limestone process. Early evaluations made before the kinetic data were available and using a moving bed design were quite favorable. However, a later evaluation which included the kinetic data and a counter flow design indicated a negative energy incentive. Favorable capital and operating costs have been found for nahcolite by dry injection techniques. The possible use of a dry injection/MDLP technique might offer similar advantages and thus needs to be evaluated. Since each assessment is extremely dependent on the engineering design used, a detailed systems analysis must be performed before any final conclusions as to possible economic advantages or disadvantages can be made.

Additional experimentation is needed to assess the efficiency of a limestone bed on particulate removal and as a combined NO_x/SO_x removal device. Numerous studies have been reported in which calcium salts and sulfite/bisulfite ions were responsible for the catalytic decomposition of nitric oxides[17]. Evidence for combined NO_x/SO_x removal would greatly enhance the interest in MDLP.

REFERENCES

1. Dickerman, J.C. et al. Evaluation of Dry Alkali for FGD Systems. Prepared for Pacific Power and Light Company and Public Service Company of Colorado by Radian Corporation, Austin, TX. March 1978.

2. Dustin, D. F. Report of Coyote Pilot Plant Test Program. Test Report, Canoga Park, CA, Rockwell International, Atomics International Div. November 1977.

3. Bechtel Corporation. Evaluation of Dry Alkalis for Removing Sulfur Dioxide from Boiler Flue Gases. Electric Power Research Institute, Palo Alto, CA, EPRI FP-207. October 1976. Pages 18 and 19.

4. Shale, C.C., and W.G. Cross. Modified Dry Limestone Process for Control of Sulfur Dioxide Emissions. U.S. Pat. 3,976,747. August 24, 1976.

5. Nesbitt, F.L. Kinetic Study of Flue Gas Desulfurization by Limestone. Thesis, Graduate School, West Virginia University, Morgantown, WV. 1978.

6. Westmoreland, P.R. et al. Co[redacted]ve Kinetics of High-Temperature Reaction Between H_2S and Selected Metal Oxides. Environ. Sci. Technol. 11:488 (1977).

7. Schroeder, L.C. Sulfur Dioxide. New York, Permagon Press, Inc., 1966. p. 63.

8. Roberts, D.L. Sulfur Dioxide Transport Through Aqueous Solutions. Ph.D Thesis, California Institute of Technology, Pasadena, CA. January 1979. p. 165.

9. Rand, M.C. Principles of Applied Water Chemistry. In: Proc. Rudolfs Res. Conf. 4th, Rutgers State Univ., 1965. p. 380.

10. Borgwardt, R.H. Kinetics of the Reaction of SO_2 with Calcined Limestone. Environ. Sci. Technol. 4:59 (1970).

11. (a) Greer Limestone Co., Morgantown, WV. (b) Limestone No. 1359, Grove Limestone Co., Stephens City, VA.

12. (a) Dolomite No. 1341. Environmental Protection Agency, Department of Health, Education and Welfare, Cincinnati, OH 45227.
(b) Charles Pfizer and Co., Inc., Minerals, Pigments, and Metals Division, Gibsonburg, OH.

13. Rosenberg, H.S. Chemical Process Development Section, Battelle Columbus Laboratories, Columbus, OH. Personal communication.

14. Process Evaluation Group. Modified Dry Limestone Process for Removal of SO_2 from Powerplant Flue Gases, An Economic Evaluation. Report No. 71-26, U.S. Department of the Interior, Bureau of Mines. February 1971.

15. Rao, A. K. Modified Dry Limestone Process Engineering Assessment, Morgantown Energy Technology Center, Department of Energy. Prepared by TRW Energy Systems Planning Division, Morgantown, WV. September 1978.

16. Lutz, S.J. *et al*. Evaluation of Dry Sorbents and Fabric Filtration for FGD. EPA-600/7-79-005, Prepared by TRW, Inc., Durham, NC for Industrial Environmental Research Lab. Research Triangle Park, NC, Jan. 1979.

17. For example, see English Patent No. 1,134,881. November 27, 1968.

TABLE 1

KINETIC PARAMETERS FOR THE ABSORPTION OF H_2O+SO_2 ON LIMESTONE

$E_a = 13.0$ kcal/mole

Temp (°c)	$(dw/dt)_o$	R_o (mole/mg min)	kg (cm^3/mole min)
35	.140	2.4×10^{-9}	113
38	.181	2.8×10^{-9}	133
43	.309	3.8×10^{-9}	212

TABLE II

COMPAIRSON OF CALCINED LIMESTONE WITH MDLP

	MDLP	Calcined*
E_a	13 ± 1 kcal/mole	8-18 kcal/mole†
R_o	3×10^{-6} g-mole/g sec	2×10^{-6} g-mole/g sec
A	4.1×10^{8} g-mole/g sec	2.07×10^{8} g-mole/g sec
ΔS	-7.86 cal/mole deg	
ΔH	16.2 kcal/mole	

* For calcined data R_o was 1×10^{-8} g-mole/cm^3 SO_2 at 870°C, whereas MDLP was 1×10^{-8} g-mole/cm^3 SO_2 at 38°C.

† Activation energies vary as to the type of limestone.

TABLE III

ANALYSIS OF VIRGINIA LIMESTONE FRACTIONS

Sample No.	Description	Composition, wt.-pct.			
		$CaCO_3$	$CaSO_4$-1/2 H_2O	SiO_2	Other
1	Original limestone	97.5	0.0	2.5	0.0
2	Surface material removed	5.6	90.0	2.5	1.9
3	Recovered limestone	97.5	0.0	2.5	0.0

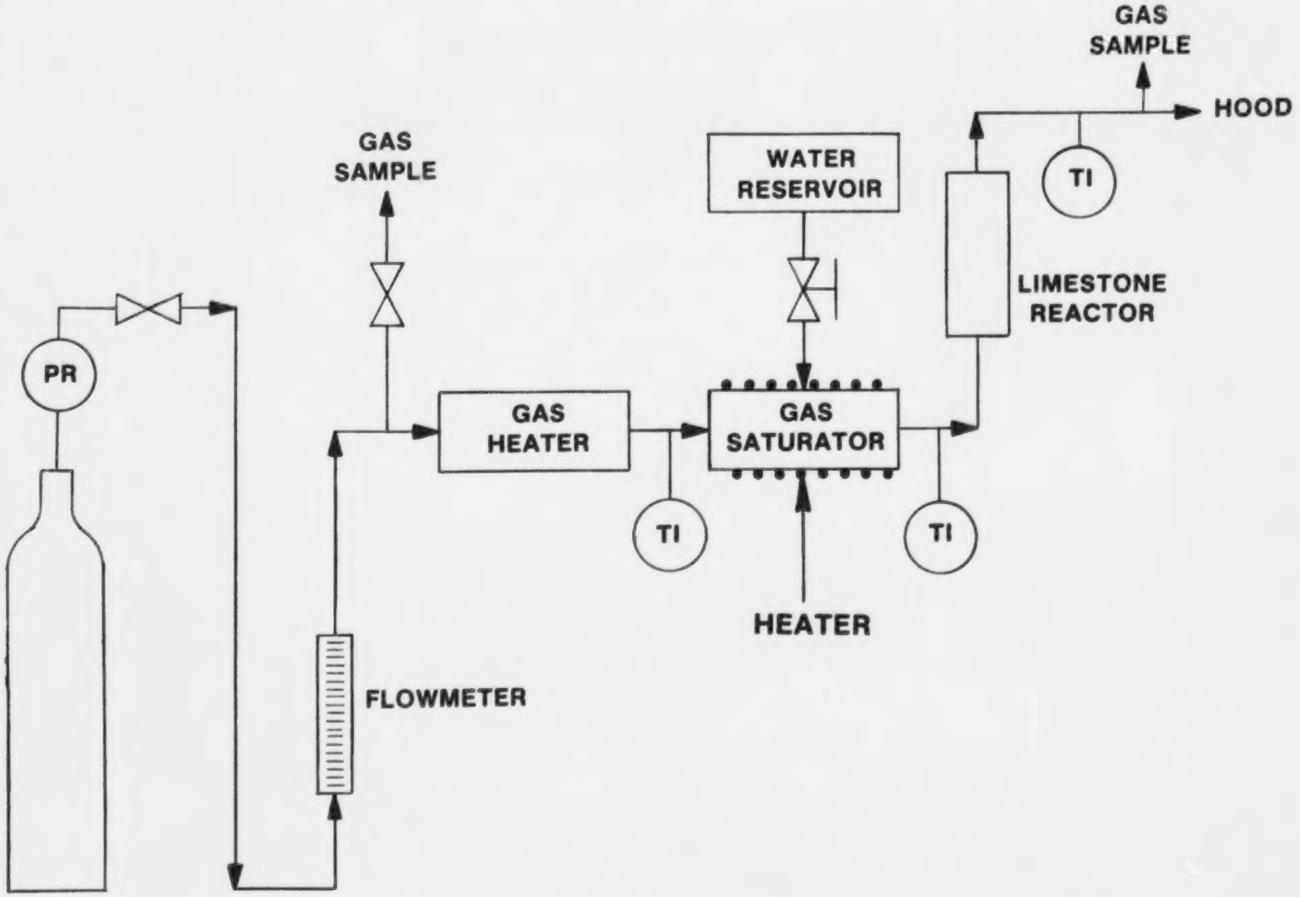

FIGURE 1 - Flowsheet for Modified Dry Limestone Process

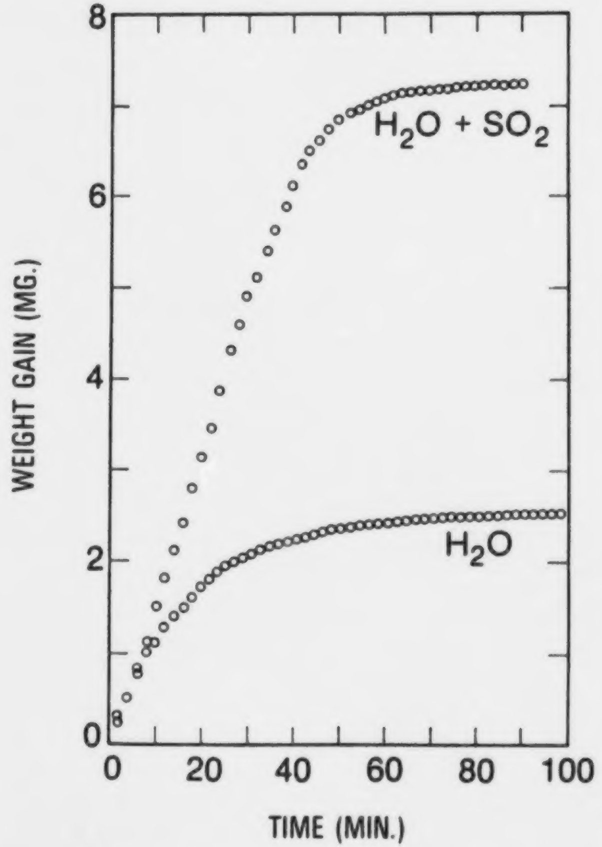

FIGURE 2 - MEASURED WEIGHT CHANGES DURING THE REACTION OF H_2O AND $H_2O + SO_2$ WITH LIMESTONE AT 100°F AND 5% SO_2
(PELLET WEIGHT = 749.8 MG.)

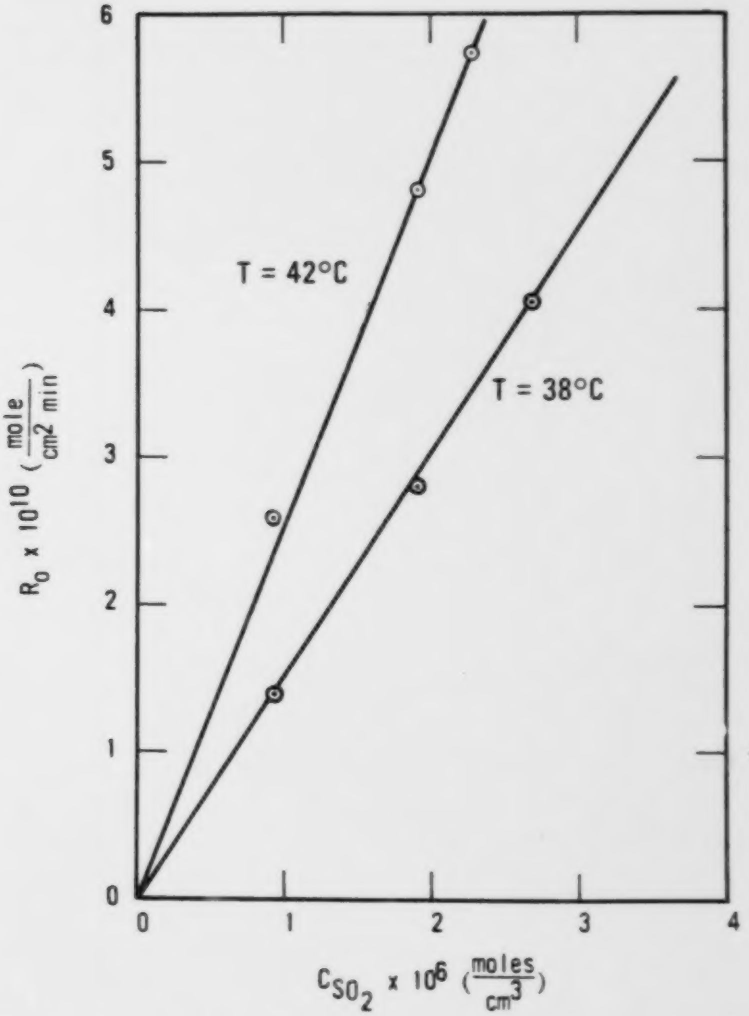

FIGURE 3 - ANALYSIS OF REACTION ORDER AS A FUNCTION OF SO_2 CONCENTRATION

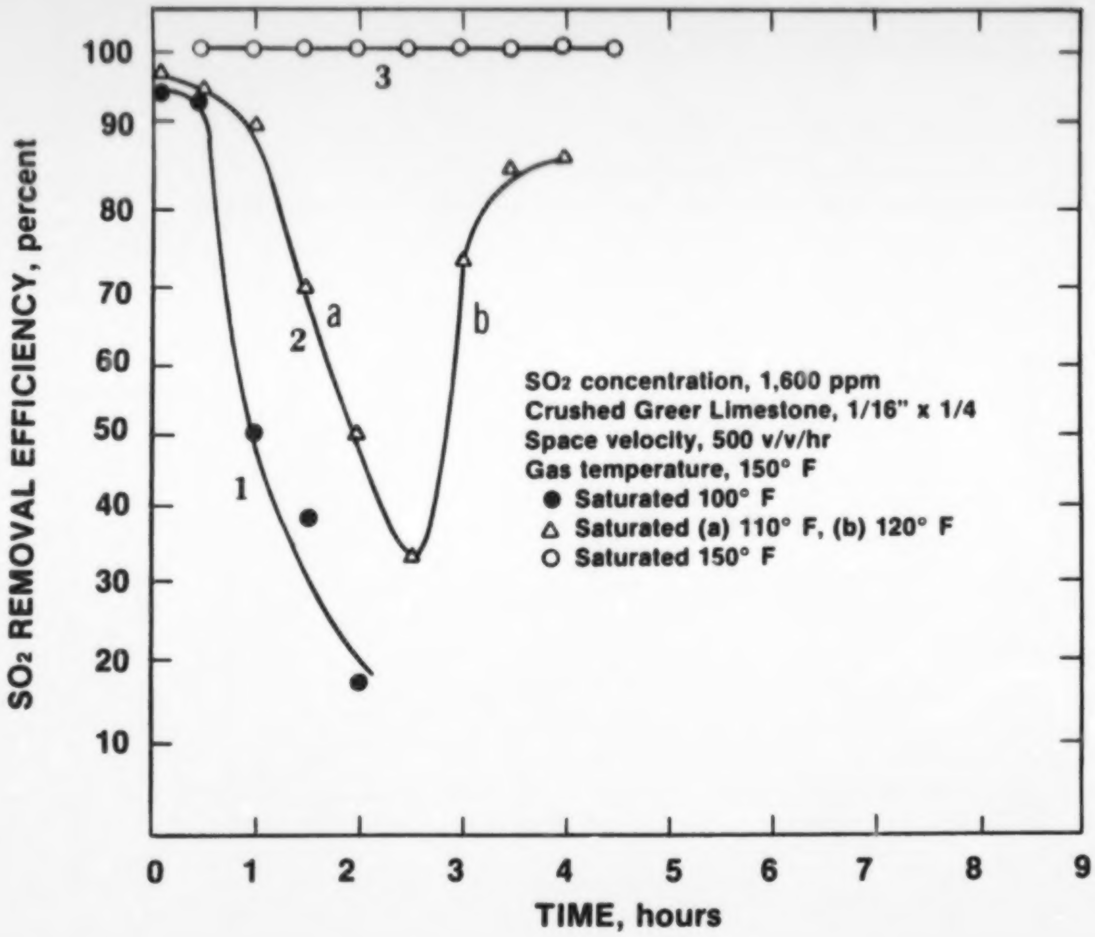

FIGURE 4 - EFFECT OF MOISTURE ON SO_2 REMOVAL BY CRUSHED LIMESTONE

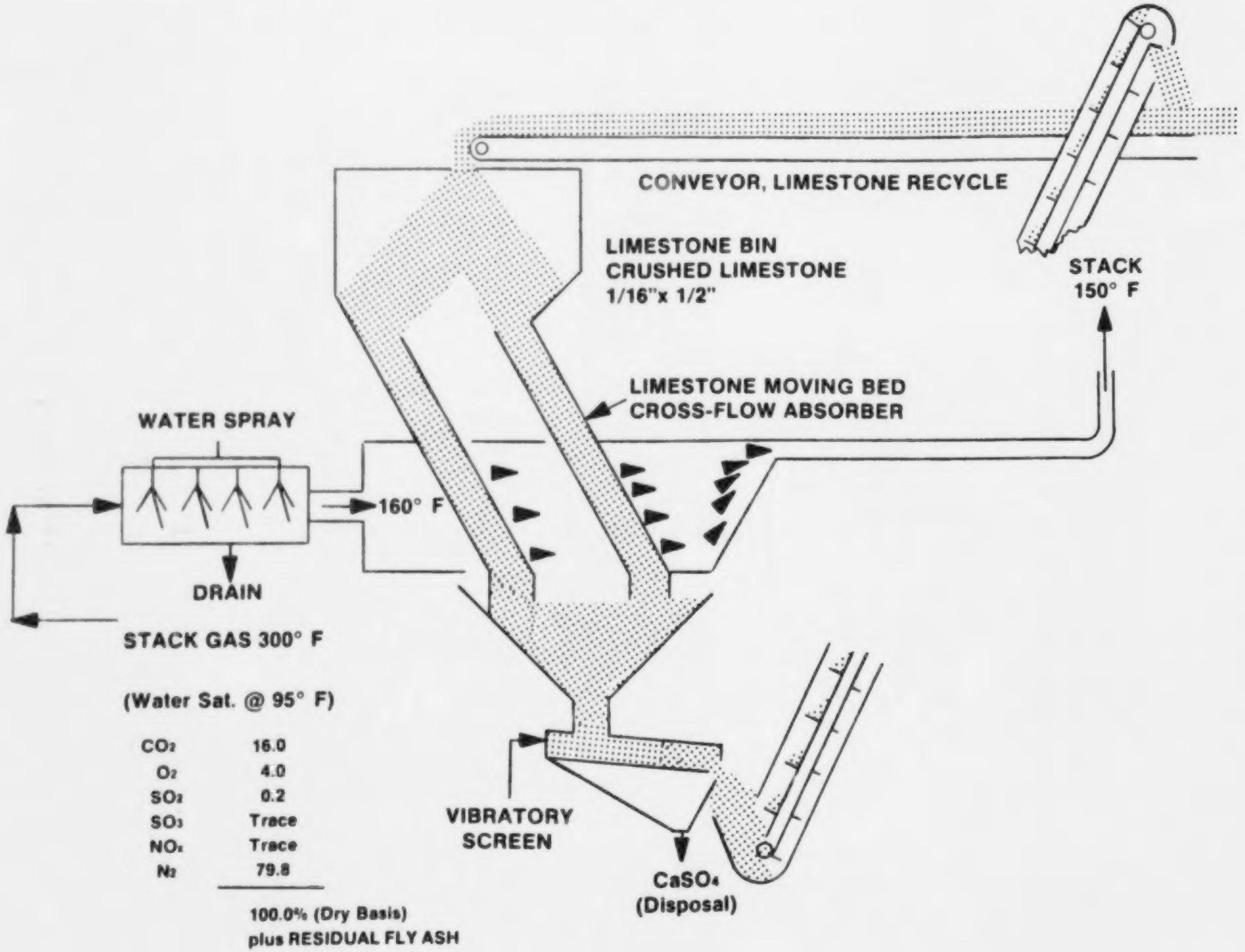

FIGURE 5 - CONCEPTUAL APPLICATION FOR THE MODIFIED DRY LIMESTONE PROCESS

SPRAY DRYER/BAGHOUSE SYSTEM FOR PARTICULATE & SULFUR DIOXIDE CONTROL, EFFECTS OF DEW POINT, COAL AND PLANT OPERATING CONDITIONS

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ABSTRACT

This paper discusses the use of a combination spray dryer and baghouse or spray dryer and electrostatic precipitator for particulate and sulfur dioxide control. Reactant compounds are injected into the spray dryer in a solution or slurry. The dry reaction products and coal fly ash are removed in a downstream baghouse or precipitator.

Several factors influence the system performance including coal moisture and sulfur content, plant altitude, dew point temperature approach and boiler design. A TI-59 computer program was developed to perform combustion calculations and to calculate dew point, spray dryer operating temperature drop and chemical spray rates. Operating limits of coal sulfur content and sulfur dioxide removal were determined. Graphs are presented which can be used to study a wide variety of application conditions.

It is concluded that applicability of the spray dryer/baghouse concept is limited by flue gas temperature, startup conditions and required sulfur removal. Boiler design changes or extending the averaging period for sulfur dioxide removal could alleviate the limitations.

SPRAY DRYER/BAGHOUSE SYSTEM
FOR PARTICULATE & SULFUR DIOXIDE CONTROL,
EFFECT OF DEW POINT, COAL AND
PLANT OPERATING CONDITIONS

INTRODUCTION

Interest has increased rapidly in the concept of a combination spray dryer/baghouse or spray dryer/electrostatic precipitator for removal of sulfur dioxide and particulate from coal burning plants. Several such systems are now on order and one will soon be in operation. The objective of this paper is to provide information regarding the limits of applicability of this system. The limit is determined by system temperature drop and the need to stay above the flue gas adiabatic saturation temperature.

The limits are summarized by the graphs which can be used to study a wide range of conditions.

SPRAY DRYER SYSTEM DESCRIPTION

The spray dryer for sulfur dioxide removal is located upstream of a fabric filter or electrostatic precipitator. The flue gas passes through the dryer vessel and chemical solution or slurry is sprayed into the dryer. The absorbent reacts with sulfur dioxide while in the liquid solution or slurry.

The liquid droplets dry before leaving the vessel and the dry reaction products and fly ash are removed from the flue gas by the downstream baghouse or precipitator. Some sulfur removal also occurs in the dry phase if a baghouse is used. Spray dryer systems presently on order will use sodium carbonate or calcium oxide (calcium hydroxide after mixing with water) as the absorbent.

The spray dryer system reduces the flue gas temperature to a level near the adiabatic saturation level (near the moisture dew point for typical spray dryer conditions). The system must be operated above the saturation temperature to assure that the droplets dry before reaching the vessel walls or entering the downstream particulate collector.

Creation of a fine spray is achieved by several methods being offered by various system suppliers. These include high speed rotary atomizers, steam atomizers and high pressure nozzles.

A key to efficient utilization of chemical is to spray enough liquid into the system to bring the flue gas close to the saturation temperature. This increases the droplet drying time which increases chemical utilization (reduces chemical consumption) because the reaction is more efficient in the wet phase. Utilization is defined as the percent of the absorbent reacting with sulfur dioxide. Thus, higher utilization rates are desirable.

Sodium carbonate solutions must be limited to concentrations under 30% due to solubility limits. A calcium hydroxide slurry is also limited to approximately 30%* (based on calcium oxide) due to heat generation when slaked with water and by grit removal requirements. Thus the amount of absorbent which can be sprayed into the system is limited because of the concentration limits and the need to stay above saturation temperature. This limits the amount of sulfur dioxide which can be removed from the flue gas. Thus there is a coal sulfur content limit for a given required percent sulfur dioxide removal.

The coal sulfur limit is dependent on many factors including coal hydrogen and moisture content, boiler excess air, plant altitude, duct pressure and boiler exit gas temperature. An objective of this paper is to show the relative importance of each of these variables and to establish sulfur limits. To do this, a computer program was developed and curves were drawn for typical lignite, sub-bituminous and bituminous coals.

THE COMPUTER PROGRAMS

The computer programs were developed for the Texas Instruments TI-59 calculator/computer with magnetic card recording capability. The programs fit onto three magnetic cards (each approximately 0.6" by 2.7"). Two computer programs were developed. The first is a combustion calculation program to determine gas flow rates and flue gas analysis. The second program uses the output of the first for spray dryer calculations.

The 418 step combustion program input and ouput consists of:

Input:

1. Fuel analysis
2. Percent excess air
3. Barometric pressure
4. Duct pressure

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*Concentrations of about 40% have been piloted by recycling unused absorbent and fly ash.

5. Boiler heat input rate
6. Gas temperature

Output:

1. Gas flow rate, weight
2. Gas flow rate, volume
3. Gas molecular weight and density
4. Flue gas analysis

The 547 step spray dryer program input and output consists of:

Input:

1. Gas flow rate
2. Sulfur dioxide flow rate
3. Flue gas analysis
4. Plant altitude
5. Duct pressure
6. Required sulfur dioxide removal, %
7. Percent weight absorbent in solution or slurry
8. Absorbent molecular weight
9. Absorbent percent utilization
10. Flue gas temperature

Output:

1. Absorbent flow rate
2. Water flow rate
3. Final flue gas temperature
4. Flue gas specific heat
5. Flue gas moisture dew point
6. Temperature margin above dew point
7. Flue gas molecular weight
8. Flue gas moisture content
9. Flue gas vapor pressure.

The method of spray dryer calculations is as follows. Moisture due point temperature is approximated by:

Dew point $(^{o}F) = e^{(\ln P + 14.562)/3.3}$
where $P = (29.92^{*} - \text{altitude in feet}/1000) \times (\%\ \text{vol. moisture}/100)$.

This formula is sufficiently accurate over the range of conditions of interest here. Dew point temperature is very close to the adiabatic saturation temperature for typical spray dryer conditions.

Flue gas specific heat is calculated for each gas constituent and an overall specific heat is calculated based on the percentage of each gas constitutent in the flue gas. The form of the specific heat equations is: $Cp = a + b\,T - CT^2 - d/T^2$

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* +0.0735 x ("WG duct pressure)

where coefficients a, b, c and d are given for each gas constituent in several references including "Manual for Process Engineering Calculations" by Clarke and Davidson.

The heat given up by the flue gas to evaporate the spray water consists of the energy to raise the water and absorbent to dew point, latent heat of evaporation and the heat to raise the evaporated liquid and absorbent to the final temperature. The latet heat of evaporation is calculated by a linear equation approximation based on steam table data over the range of interest.

The forgoing was combined to estimate flue gas final temperature and moisture dew point.

PERFORMANCE GRAPHS

Figures 1 through 7 show flue gas data and spray dryer performance limits for three classes of coal: lignite, subbituminous and bituminous. Typical coal analyses used for this study are as follows:

	Lignite	Sub-Bitum.	Bitum.
Carbon	37.48	53.56	72.0
Hydrogen	3.36	3.80	4.40
Nitrogen	0.64	1.08	1.40
Oxygen	8.90	10.40	3.60
Water	40.00	20.15	8.00
Sulfur	0.86	0.84	2.00
Ash	8.76	10.17	8.60
Btu/lb	6,500	9,400	12,800

As sulfur content was varied for study, other constituents were adjusted proportionally. The above analyses were selected as typical for each coal class.

The attached figures were developed for the above coals. Figure 1 shows the effect of moisture content, duct pressure, plant altitude and percent excess air on flue gas moisture dew point. Figure 1 is for conditions prior to spray dryer operation. Figure 2 shows flue gas temperature drop with spraying of a 30% sodium carbonate solution or a 20% calcium hydroxide slurry. Calcium hydroxide concentration is expressed as percent calcium oxide. Data are shown for a range of sub-bituminous coal sulfur contents, percent sulfur dioxide removals and chemical utilization rates. Figure 3 shows coal sulfur limits for a sodium carbonate solution spray dryer. This figure is for a 30% solution. Usually the solution would be more diluted to obtain temperatures near the dew point. A concentration of 30% is shown to indicate the limit of tolerable coal sulfur content. Figures 4, 5 and 6 show sulfur limits for calcium hydroxide slurry dryers. These figures are arranged differently from Figure 3 because three different slurry concentrations are shown.

Figures 3 through 6 are for a dryer exit temperature 40°F (4.4°C) above the flue gas moisture dew point. Some believe that much closer approaches can be used without substantial risk of baghouse or precipitator fouling. An example will be presented to show the effect of decreasing the margin above dew point.

WHAT THE FIGURES SHOW

Figures 1 through 7 include a large number of curves. This is necessary because the number of variables is large. Curves are drawn for two absorbents, three flue gas inlet temperatures and three classes of coal. Among the information shown are:

1. Flue gas moisture content upstream of the spray dryer varies from 7-17% for the three coals selected. This significantly affects the flue gas moisture dew point (Figure 1). Lignites would have a higher moisture dew point and thus lower spray dryer sulfur removal capability. Fortunately, lignite often has less sulfur than bituminous coal. Bituminous coal often has the highest sulfur content but a lower moisture content. Thus more heat would be available above the moisture dew point and more absorbent could be added.

2. Significant differences in sulfur removal capability for the three classes of coal are shown on Figures 3 through 6. Percent chemical utilization is a key factor. For a given chemical concentration, increased absorbent flow will require increased water flow. Dew point approach limits the amount of chemical and water that can be sprayed into the system. A higher percent utilization will result in an ability to handle higher coal sulfur contents.

It is not the purpose of this paper to establish absorbent utilization percentages. These are determined by the system suppliers and vary with operating conditions and system design. Values of 70 to 95% are typical. Recycle of fly ash and unused reactant can improve utilization.

3. Duct pressure (spray dryer inlet pressure) influences dew point slightly whereas plant altitude and boiler excess air have a significant effect (Figure 1). Lower duct pressure, higher plant altitutde and increased excess air are beneficial to spray dryer system capability because of larger available temperature drop.

4. The curves can be used in conjunction with each other. For example, Figure 3 shows data for sub-bituminous coal for a plant at sea level and operation of the spray dryer at an exit temperature 40°F above dew point. For 90% sulfur dioxide removal, if 90% absorbent utilization is assumed with 250°F flue gas, the figure indicates that 2.9% coal sulfur content is the maximum that can be used.

What is the limit if the design is for 20°F above dew point rather than 40°F? Figure 2 shows a 20°F drop in temperature can handle about 0.7% sulfur. This, added to 2.9%, would give a capability to handle 3.6% sulfur coal. What if the plant is at 6,000 ft altitude rather than at sea level? Figure 1 indicates that the dew point would be reduced by about 8°F. Figure 2 indicates a capability to handle 0.3% more sulfur or 3.9% total.

The above are approximations however, the more accurate computer program gives a sulfur limit within 0.1% of the above. It should be noted that flue gas temperature drops for lignite and bituminous coals would not be exactly the same as those shown on Figure 2 because of flue gas composition differences.

5. Figures 3 through 6 indicate maximum tolerable sulfur contents for a variety of conditions. For example if 80% utilization of a 20% calcium oxide slurry is achieved for a case requiring 90% sulfur dioxide removal from 300°F flue gas; lignite could have up to 3.1% sulfur (Figure 4), sub-bituminous up to 4.4% sulfur (Figure 5) and bituminous coal in excess of 6% sulfur (Figure 6). It should be noted that there has not been pilot plant demonstation with high sulfur coal.*

6. Figure 7 shows the effect on maximum sulfur content with closer approach to dew point for lignite and sub-bituminous coals. Closer approach would also increase absorbent percent utilization and thus further increase maximum tolerable sulfur content. The absorbent percent utilizations shown are illustrative and are not meant to imply that they would occur.

7. The figures are not affected by any additional sulfur dioxide removal in a downstream baghouse. The baghouse would increase absorbent percent utilization. The higher utilization would be used on the figures to determine the maximum tolerable sulfur content.

BOILER INFLUENCE ON SYSTEM CAPABILITY

Figures 3 through 6 indicate a limited sulfur dioxide removal capability when flue gas is at a low temperature (200°F for example). The lower temperature limits the amount of water and absorbent which can be sprayed into the system. Operating limits are more likely to occur during each boiler startup or during low load operation because of probable lower flue gas temperature during these conditions.

Methods of alleviating this problem include the following:

1. Reducing the amount of boiler economizer surface. This would increase the spray dryer inlet temperature but would decrease boiler efficiency. This cost penalty could be severe because it would apply at high loads as well as at low loads.

*There have been some tests where flue gas was spiked with SO_2.

2. Install steam coil heaters to increase primary air and/or secondary air temperature. The steam heaters would only be used when operating at low loads.

3. Install steam coil heaters upstream of the spray dryer. Potential for heater fouling should be evaluated.

4. Bypass some of the flue gas around the air preheaters. This may not be acceptable for some installations because the air preheater cold end temperature must be maintained above the minimum recommended level to prevent corrosion. Also, the primary air temperature could be too low to dry the coal in the pulverizers.

5. Operate the spray dryer closer to dew point and reheat the dryer discharge to protect the baghouse or precipitator.

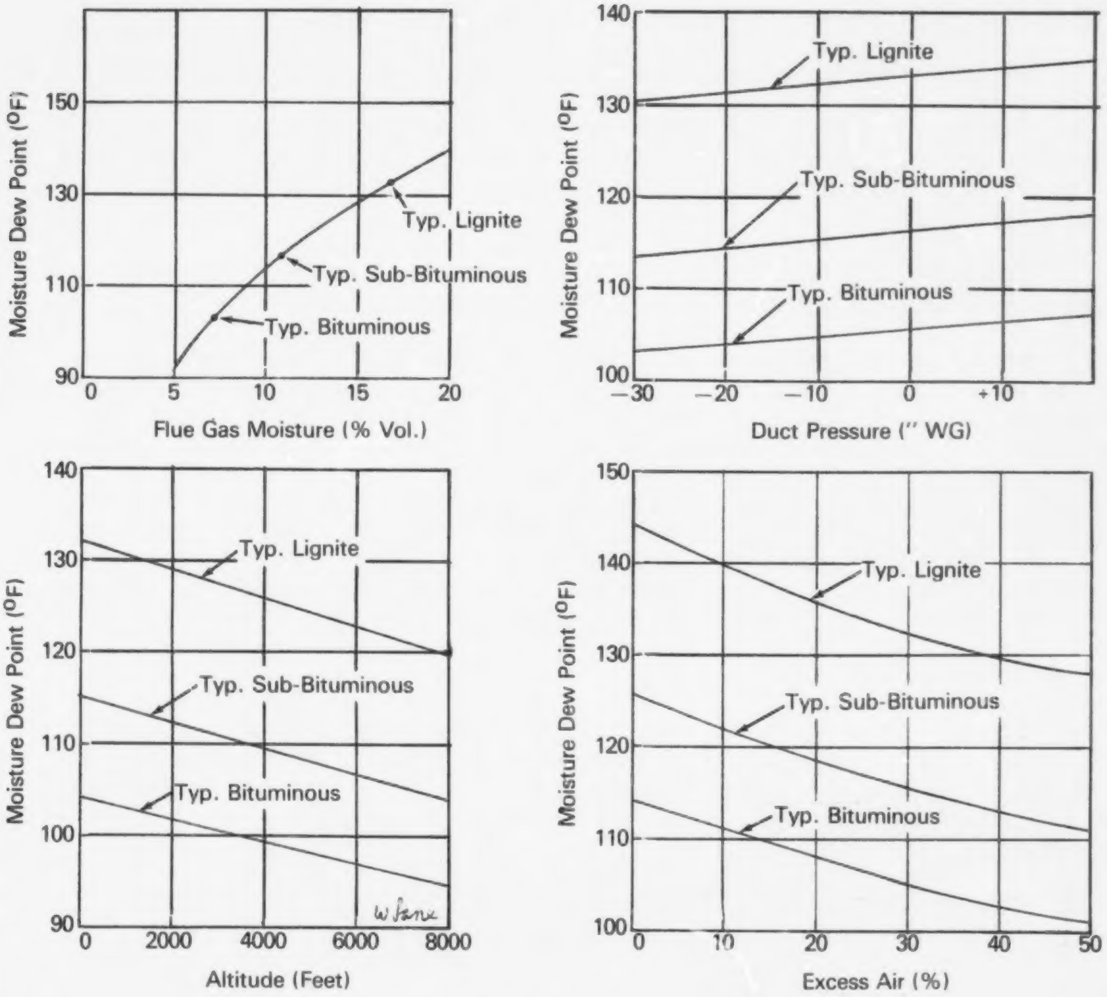
6. Each of the above would increase the plant heat rate (coal consumption). As an alternate to the above, sulfur dioxide removal philosophy could be altered. Lower spray rates and sulfur dioxide removal during startup may be allowable. Applicable laws should be considered for each case. The new federal emission limit allows thirty day averaging of sulfur dioxide emissions. Local regulations should also be considered. If higher emissions during startups can be averaged with lower emissions during the remainder of the averaging period, boiler desing changes or a plant heat rate penalty may not be required.

OTHER COMMENTS

Again, it is not in the scope of this paper to establish what absorbent utilization can be expected. This is a key in determining sulfur limit capability. Much pilot plant testing has been done and much more is going to be done by several suppliers.

The spray dryer will have an influence on the baghouse or precipitator. Gas volume and temperature will decrease, moisture content will increase, inlet grain loading will increase, particle size distribution and ash electrical resistivity will change. Thus far, system suppliers report no detrimental effect on pilot baghouse operation. The effect on precipitator operation may be beneficial in some cases and detrimental in others. Further pilot testing is warranted and will be conducted this year.

At this time, the future of this method of sulfur dioxide control looks promising. It is hoped that operational experience with the first units will justify the high level of optimism prevalent at this time.



Notes to Above Figures

1. Dew points are with no water spray.
2. Unless otherwise noted, dew points are at sea level, −16'' WG duct pressure and 35% excess air.

Figure 1. Flue gas moisture dew point related to plant conditions.

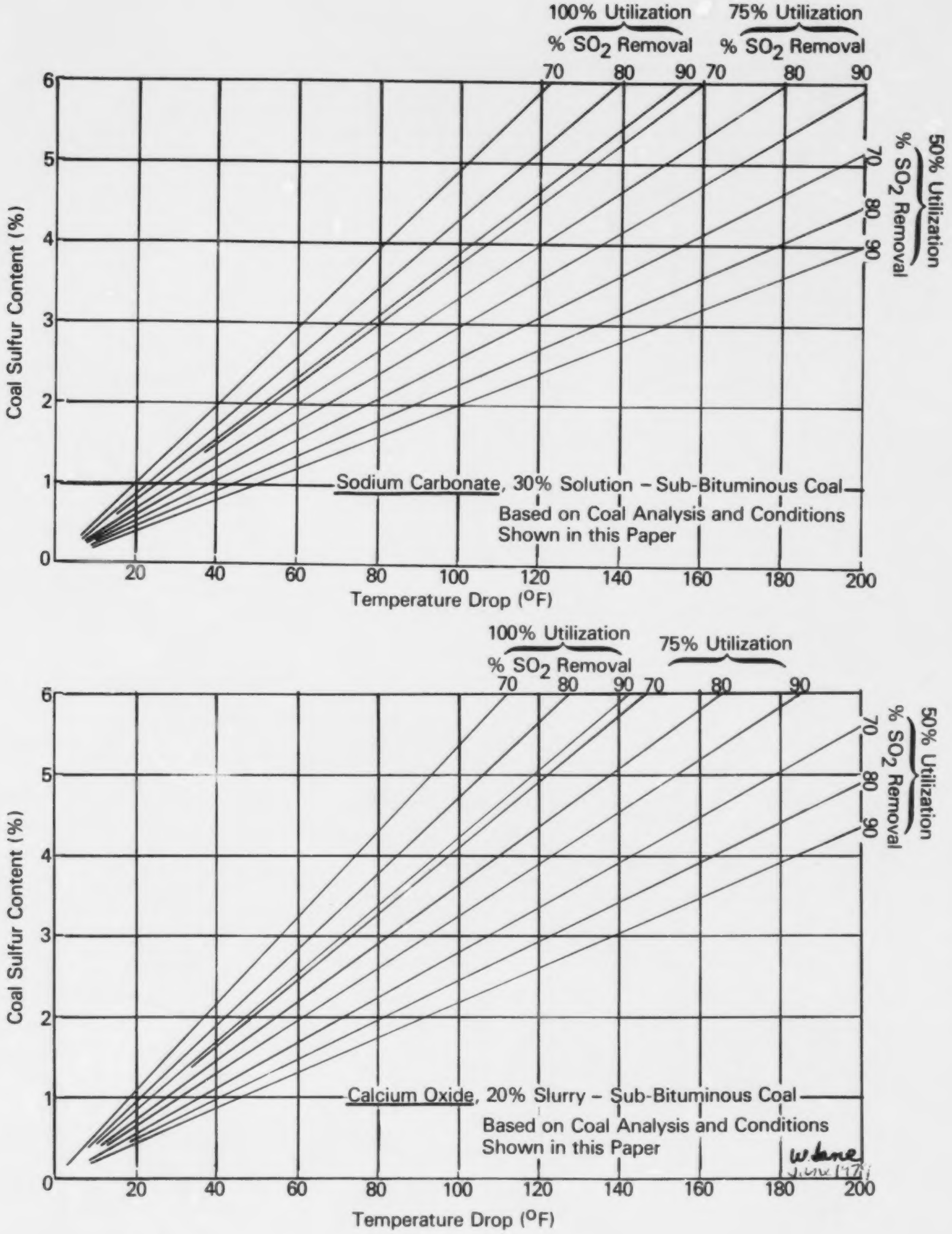
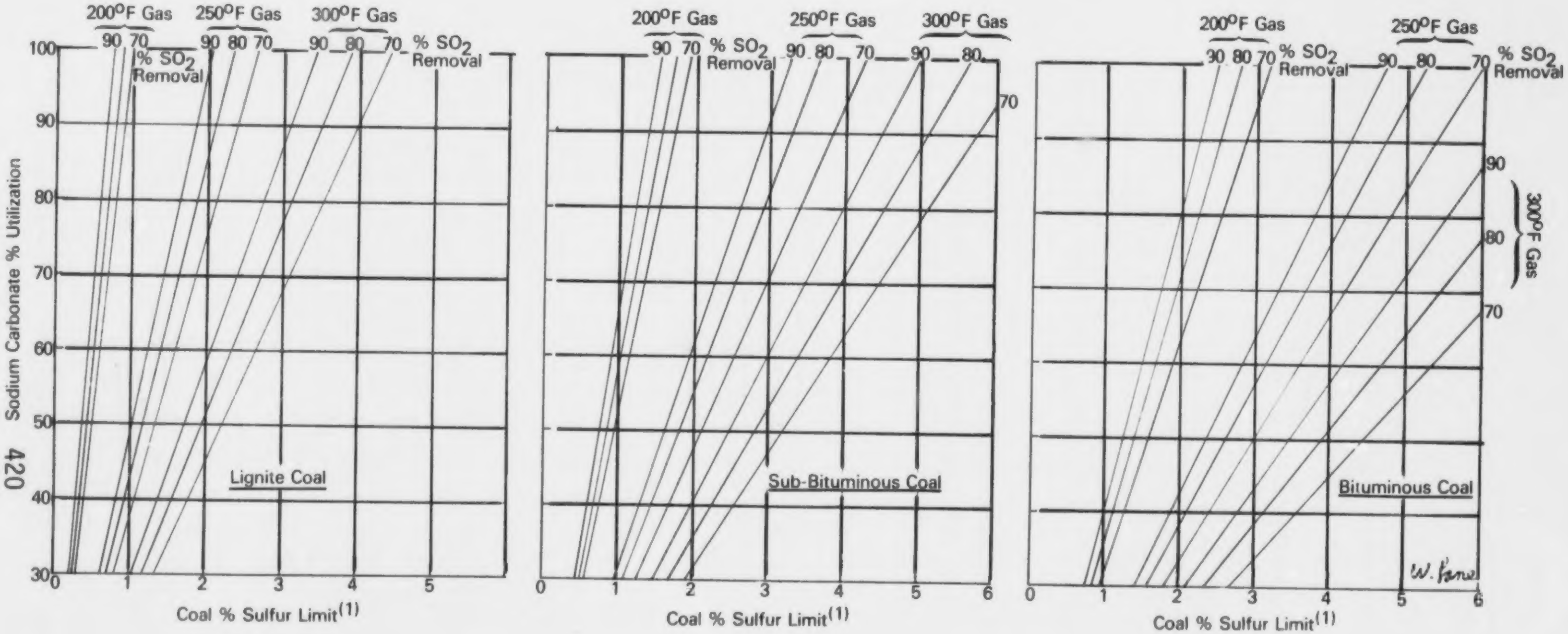


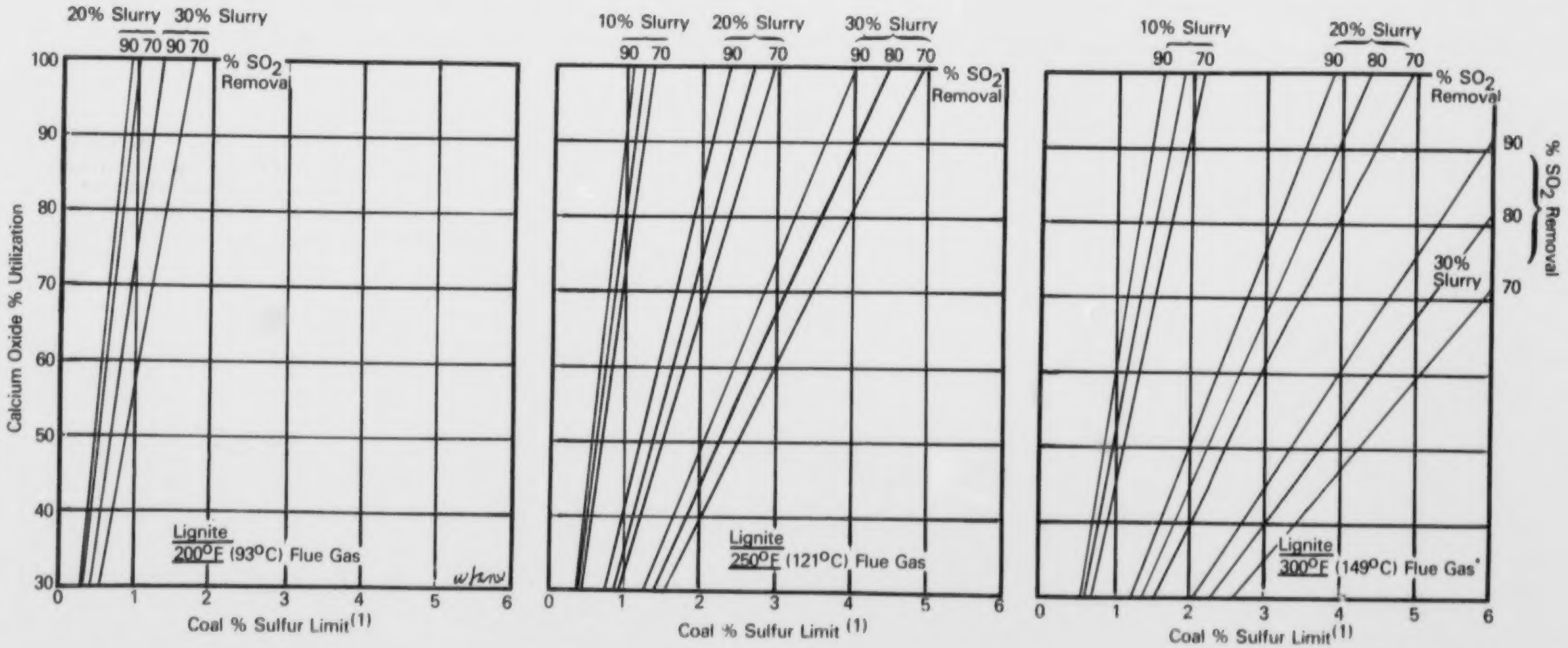
Figure 2. **Spray dryer temperature drop related to coal sulfur content for sodium carbonate and calcium oxide absorbents.**



NOTES

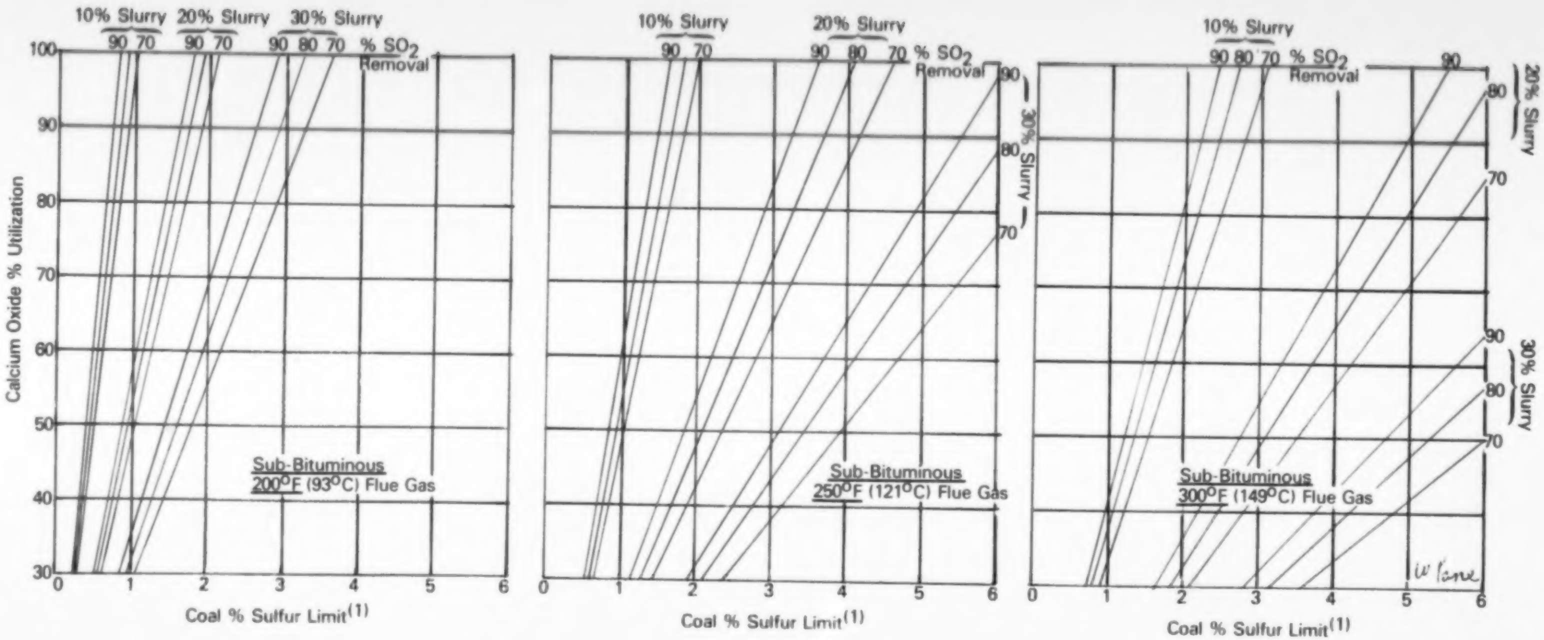
(1) To stay 40°F (4.4°C) above moisture dew point
(2) Based on sea level ambient pressure – 16" WG duct pressure and 35% excess air
(3) Sodium carbonate solution is 30% concentration
(4) Based on coal analysis shown in this paper

Figure 3. Coal sulfur content limit related to sodium carbonate utilization for three types of coal.



Notes
(1) To stay 40°F (4.4°C) above moisture dew point.
(2) Based on sea level ambient pressure, – 16" WG duct pressure and 35% excess air.
(3) Based on coal analysis shown in this paper

Figure 4. Coal sulfur content limit for lignite using calcium oxide absorbent for three flue gas temperatures.



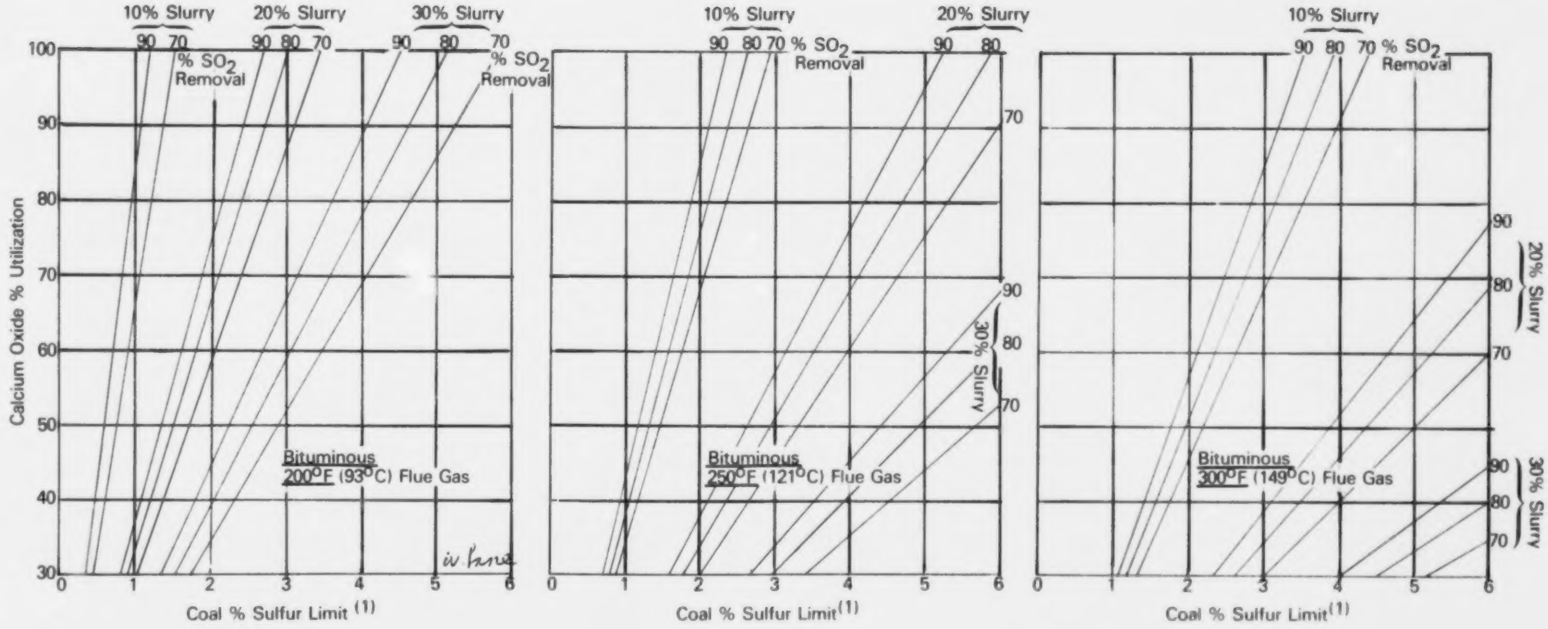
Notes

(1) To stay 40°F (4.4°C) above moisture dew point

(2) Based on seal level ambient pressure, – 16" WG duct pressure and 35% excess air

(3) Based on coal analysis shown in this paper

Figure 5. Coal sulfur content limit for sub-bituminous coal using calcium oxide absorbent for three flue gas temperatures.



NOTES

(1) To stay 40°F (4.4°C) above moisture dew point

(2) Based on sea level ambient pressure – 16" WG duct pressure and 35% excess air

(3) Based on coal analysis shown in this paper

Figure 6. Coal sulfur content limit for bituminous coal using calcium oxide absorbent for three flue gas temperatures.

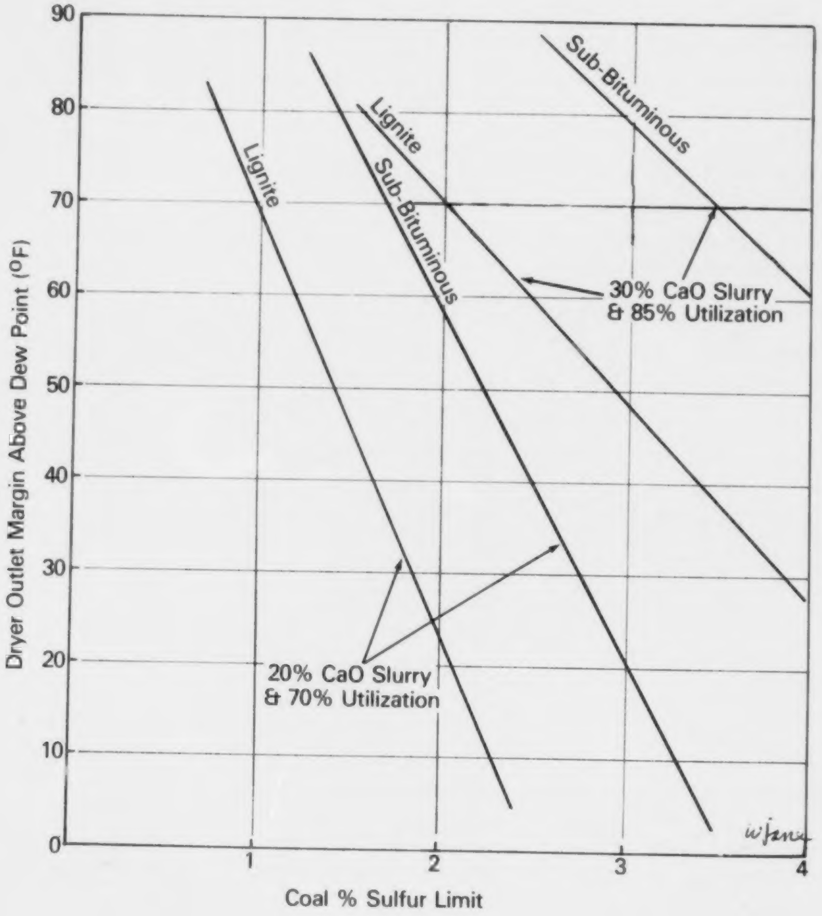


Figure 7. Coal sulfur content limit related to dew point approach for 250° flue gas and 90% SO_2 removal.

SELECTION, PREPARATION AND DISPOSAL OF SODIUM COMPOUNDS FOR DRY SO_x SCRUBBERS

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ABSTRACT

A program has been initiated to assess an SO_2 removal method wherein dry powdered sodium compounds are injected into the gas stream ahead of the baghouse filter. The compounds are collected on the surface of the filter bags for reaction with the gaseous SO_2. Initial program efforts include a survey of suitable and available sodium compounds, methods of preparing the compounds for injection, and an investigation of environmentally acceptable methods of disposal.

SELECTION, PREPARATION AND DISPOSAL OF SODIUM COMPOUNDS FOR DRY SO_x SCRUBBERS

INTRODUCTION

The increasing use of high-performance fabric filters for removing fly ash from coal-fired boilers instigated the investigation of dry alkalis for removing SO_2 from flue gas. The possibilities of such a process were suggested by the aluminum industry's success with a dry additive fabric filter collector system for the control of gaseous and particulate fluorides in the aluminum potline effluent. Subsequently there have been a number of investigations of ways to remove SO_2 with solid sorbents.

The sorbents have been various limestones or dolomites, quicklime, hydrated lime, manganese dioxide, sodium bicarbonate, sodium carbonate, and potassium permanganate. Investigations have confirmed that only sodium carbonate and sodium bicarbonate have shown good capability for reducing SO_2. Figure 1 schematically presents the key features of a system that would inject sodium compounds into the flue gas after the preheaters.

Considerable economic incentive exists for developing a dry sodium SO_2 scrubbing system in view of current costs of wet SO_2 scrubbing systems. Using data from a recent study by Genco, et al (1975)[1] (with escalation to 1979) indicates an installed capital cost of about $6 per kilowatt for the dry sodium crushing, grinding and injection system compared to current costs of at least $70 per kilowatt for a wet scrubbing system. The baghouse cost was not included in the dry sodium system since all current wet scrubbing systems also require a comparable, separate fly ash collection device. Escalated operating costs for the dry SO_2 scrubber (again without baghouse) are 1.5 mills/KWH compared to an estimated, and escalated, 2.2 mills/KWH for a wet limestone scrubbing system.

To assure utility acceptance of a dry SO_x removal system by injecting dry sorbents upstream of a baghouse filter, it is essential to identify a near-term and long-term supply of sorbents. Previous testing has shown the apparent superiority of sodium bicarbonate in the form of nahcolite for reaction with SO_x/NO_x in the dry form. Other candidate sorbents were evaluated as alternates considering the current availability of nahcolite.

To prepare the sodium compounds for use in the dry SO_x removal systems, they must be reduced to fine powders for injection and to increase the

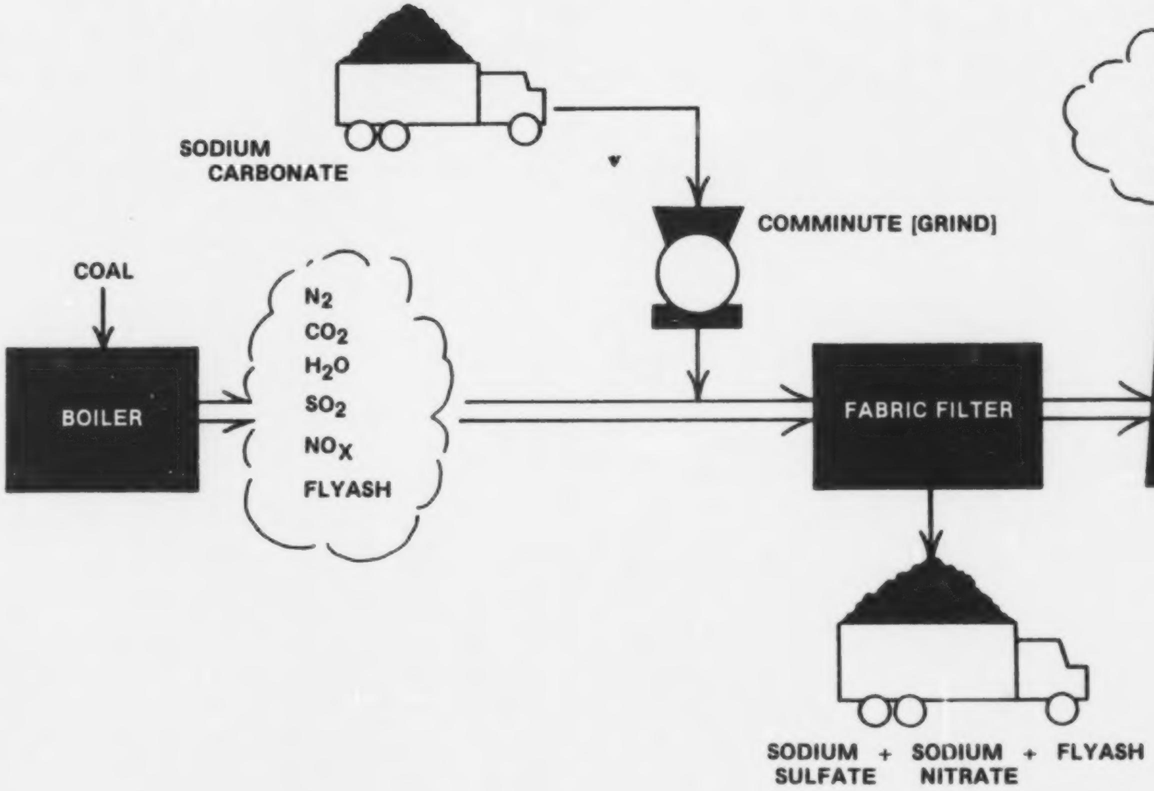

FIGURE 1

"DRY SCRUBBING" WITH SODIUM SALTS

surface area for improved chemical resistivity. Currently, tests are under way to evaluate mechnical grinding and thermal comminution.

Several methods of disposal for the spent sodium compounds from dry SO_2 removal systems are being considered, including clay isolation land fill and insolubilization by chemical methods and by sintering.

POTENTIAL SOURCES OF SODIUM COMPOUNDS

Nahcolite

Nahcolite ore is a naturally occurring mineral containing 70 to 90% sodium bicarbonate. It is found almost exclusively associated with oil shale. Vast resources of oil shale and associated nahcolite exist in the Eocene Green River formation in the Piceance Creek basin of northwest Colorado. According to the United States Bureau of Mines, this area is conservatively estimated to contain 32 billion short tons of nahcolite. In 1976, the Bureau launched a multi-year oil shale research and testing program to identify and resolve environmental problems associated with the development and mining of the deep deposits of oil shale and associated saline materials. A ten-foot diameter pilot mine shaft was completed in 1978 at the Bureau's research facilities in Horse Draw, Rio Blanco County, Colorado.

Vast resources of the sodium minerals, nahcolite ($NaHCO_3$) and dawsonite ($NaAl(OH)_2CO_3$), exist in the rich oil shale of the Green River Formation. The significant quantities of the sodium minerals are restricted to the lower portion of a geologic unit called the Parachute Creek Member. The nahcolite-bearing oil shale reaches a maximum thickness of about 1130 feet at the chemical depositional center for the nahcolite, dawsonite, and the associated halite (NaCl). The top of the sodium mineral-bearing section ranges in depth from approximately 1400 to 2000 feet below the ground surface. Nahcolite occurs in four distinctive forms:

1. Brown microcrystalline beds
2. White coarse-grained beds
3. Laterally continuous units of fine-grained crystals disseminated in oil shale
4. Disseminated nonbedded crystalline aggregates

In coreholes analyzed by the United States Geological Survey, the nahcolite resource ranges from a low of 174 million short tons to a maximum value of 489 million short tons per square mile. About 257 square miles are underlain by nahcolite-bearing oil shale with thicknesses in excess of 100 feet. According to the United States Bureau of Mines, this area is conservatively estimated to contain 32 billion short tons of nahcolite.

Trona

Trona contains about 50% sodium carbonates. Major trona deposits are in the Green River formation in southwestern Wyoming. The total reserves in this area are estimated at 85 billion short tons. The Green River trona is currently a major source of ore for commercial production of soda ash. Unfortunately, tax considerations (depletion allowances) do not favor the use of small quantities of trona as a raw ore.

The Owens Lake in California is a source of sodium compounds available for immediate use. The relatively small current production could be readily expanded. Depletion allowance taxes are not a problem. However, the limited quantity of sodium available means that the source is only of interim interest assuming widespread acceptance of dry SO_2 removal.

The evaporite deposit at Owens Lake is a complex mixture of sodium carbonate, sodium bicarbonate, sodium sulfate and sodium chloride including double salts, hydrates and saturated brine, all resulting from the dessication of a large saline lake that existed until about 60 years ago.

In 1917 the City of Los Angeles completed construction of an aqueduct which draws water from the Owens River. The Owens River was the principal source of water feeding the then 100-square-mile lake. Its diversion allowed the lake level to decline due to evaporation. As a consequence, its dissolved salts became concentrated until they began to precipitate onto the lake bed. When the lake finally reached a new state of equilibrium, it had shrunk to less than 40 percent of its original size, forming a solid deposit of mixed salts wet with interstitial brine.

The Owens Lake evaporite deposit covers an area of approximately 35 square miles at the lower end of the Owens Valley in Inyo County, California. The nearest town is Lone Pine which lies about 10 miles north. The elevation of the surface of the lake is about 3500 feet above sea level. The lofty Sierra Nevada range (including Mt. Whitney) rises abruptly to the West while the eastern side of the valley is formed by the lower and more arid Inyo Mountains. Precipitation averages only 4 to 5 inches per year and the net evaporation rate is about 66 inches.

The area is served by a branch line of the Southern Pacific Railroad which passes along the western edge of the lake, providing a direct rail linkage with the harbors of Los Angeles and Long Beach, a distance of roughly 240 miles. Also the U.S. Highway 395 between Los Angeles and Reno passes immediately alongside the lake.

The raw ore from Owens Lake, upgraded only by mining methods, appears attractive for use as a sorbent in the SO_2 removal system. However, it also appears attractive to upgrade the raw ore to relatively pure sodium bicarbonate. It has been estimated that 92% pure sodium bicarbonate could be produced at the Owens Lake for approximately $50 per ton compared to estimates of $17 per ton for the raw ore. This appears quite attractive assuming improved performance and lower handling and shipping costs.

Supply Prospect

Primarily because the oil shale program is still in its exploratory phase, immediate supply of nahcolite in quantity at reasonable cost is questionable. Assuming that full-scale dry SO_x/NO_x removal systems were successfully demonstrated both technically and economically, commitments from utilities on nahcolite consumption still would be needed to start the commerical mining of nahcolite.

To resolve sodium compound supply problems for immediate implementation of dry SO_x/NO_x removal systems, it is possible to use crude trona and/or high purity sodium bicarbonate upgraded from the crude dry lake ore. Production of 1.5 million short tons per year of sodium bicarbonate for 35 years is a possibility from Owens Lake.

Potential Demands

The estimated 32 billion tons of nahcolite could be used to desulfur 610 billion tons of 0.7% sulfur coal assuming the requirement of 7.5 pounds of nahcolite per pound of sulfur removed. This indicates the adequacy of the nahcolite resource since the entire reserve of western bituminous and sub-bituminous coal is estimated at 430 billion tons.

DISPOSAL OF SPENT SORBENTS

Land Fill

Possibly the simplest method for disposal of spent sorbents is the land filling technique. In this technique a combined trench and area land fill method is used. The basic building block for the land fill is the isolation cell concept, such as has been used for sanitary fill. The spent product for one working day is transported to the site, emplaced, and compacted. The day's production constitutes the basic volume for one cell. This compacted cell is completely covered with a layer of claylike material, which in turn is also compacted at the end of each working day. Therefore, the soluble spent sorbent is encapsulated in an essentially impermeable shell of silty clay or similar material. It is important that the landfill be constructed on a base of material that has low permeability so that leaching is minimized.

Chemical Fixation

The Envirotech Chemical Sludge Fixation Process is based on the patents, research, and commercial operations of the Chemfix Process. This process involves the reaction of two or more chemical additives with the waste material to form a chemically and mechanically stable solid. This inorganic chemical system has proven stability when in contact with all of the usual environmental elements of change: soil, water, air, sunlight and micro-organisms. The quantity of chemicals added to the waste usually does not increase the final volume of the solidified material by more than 10 percent; in most cases, the increase is less than 5 percent.

The particular choice, ratio, and quantities of chemicals used for any given waste treatment application depend upon three factors:

1. The waste
2. The speed of reaction require
3. The end use of the solidified material

Since the reaction process involves a gelatin stage followed by a hardening period, gelationtime is an important factor in designing the chemical parameters of the system. Desired gelation time may depend, for example, on whether the material is to be pumped for some distance after mixing and on the method of disposal. End use of the solidified waste is important because the end product can be either hard of quite soft and can be made to have varying textures. If it is to be in contact with a high water table, or even be under water, the nature of the contacting water will also determine chemical design.

The system, as it is normally used, reacts with all polyvalent metal ions producing stable, insoluble, inorganic compounds. It is also reactive with acids, certain nonmetallic ions, and some organic compounds. Nonreactive materials are physically entrapped in the matrix structure resulting from the reaction process. Because of this variety of entrapment and reaction possibilities, each system must be custom designed for the particular chemical problem presented by the waste material to be processed.

Sintering

Laboratory experiments have also demonstrated that spent sorbent can be insolubilized by mixing it with fly ash and/or bottom ash, forming an agglomerate, and sintering at about 1800°F. The sintered material may be disposed of by known landfill techniques or used as an aggregate for road beds, concrete, etc.

REFERENCES

1. Genco, Rosenberg, Anastas, Rosar and Dulin, "The Use of Nahcolite Ore and Bag Filters for Sulfur Dioxide Emission Control", APCA Journal, Vol. 25 No. 12, December 1975, p. 1244

METRIC CONVERSION TABLE

1 inch = 2.54 centimeters
1 foot = 0.3048 meters
1 mile = 1.6093 kilometers
1 square mile = 2.590 square kilometers
1 ton/square mile = 2.855 kilograms/square meter
1 short ton = 907.2 kilograms
1 dollar/ton = 0.1103 cents/kilogram

HIGH VELOCITY FABRIC FILTRATION FOR CONTROL OF COAL-FIRED BOILERS

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ABSTRACT

As a follow-up to a pilot plant study, a full scale investigation of applying high velocity fabric filtration to coal-fired boiler fly ash control was conducted. Two filter systems were separately applied to two 60,000 lb./hr. coal-fired boilers. Performance evaluations conducted over the course of a year included total mass removal efficiency and fractional efficiencies. One filtration system employed Teflon felt as the filter medium while the second system employed Gore-Tex, a PTFE laminate on PTFE woven backing. During the course of the year, a limited number of glass felt and woven glass bags were introduced into the house containing Gore-Tex.

As a separate option, the second system was outfitted entirely with woven glass bags. Preliminary results indicate acceptable performance at an air-to-cloth ratio of 6 to 1. Future plans call for utilizing one of the baghouse systems for SO_2 removal.

INTRODUCTION

For the past six years Enviro-Systems & Research, Inc. has been involved in an EPA project to determine the techno-economic feasibility of applying high velocity fabric filtration to control the fly ash emissions of an industrial coal-fired stoker boiler.[1]

The program started on a small scale in 1973 and financial participation was divided equally among EPA, Kerr Finishing Division of FabricsAmerica and Enviro-Systems & Research, Inc. The Kerr plant, located in Concord, North Carolina, served as the host site for the program while Enviro-Systems & Research designed, fabricated and installed the pilot baghouse (Figure 1). The pilot program provided a short-term screening of a number of filter media and the data gathered along with preliminary economic analysis indicated that long-term bag life and performance studies were warranted.[2] EPA at this point decided to award a contract for the full scale demonstration unit for this approach to fly ash control. The demonstration contract was awarded Fabrics-America, with Enviro-Systems & Research as the major subcontractor responsible for the design, fabrication, installation and operation of the full scale fabric filter system (Figure 2).

The purpose of the demonstration program is the testing of a full scale fabric filter system installed on an industrial coal-fired stoker boiler and data generated by the program include general operating parameters, media changes and life data and particle size removal efficiencies as a function of on-stream time.

Contract options called for the long term testing of other promising filter media and to evaluate the fabric filter system as a vehicle for the removal of sulfur dioxide

KERR - THE HOST SITE

The Kerr Finishing Division of FabricsAmerica is a textile dye and finishing plant located in the textile belt of central North Carolina.

Kerr's normal production schedule is three shifts per day, five days per week with 450-500 employees. Plant capabilities include processes to bleach, mercerize, dye, nap, finish and sanforize both cotton and synthetic fabrics, as well as cutting and preparing corduroy.

Two Babcock & Wilcox steam boilers are in operation at the Kerr facilities. Each has a design capacity of sixty thousand pounds of steam per hour and both are equipped with spreader stokers. Each boiler has a two-hour peaking capacity of seventy thousand pounds per hour. The design efficiency of these units is 82 percent. Based on the above parameters, the heat input for these units is 73.2 million BTU/hour each. Both boilers are equipped with fans for supplying draft and unit number two, the unit tapped for the pilot plant stream, has overfire steam injection for better combustion control. In January, 1973, emission tests were conducted on these boilers. The particulate emission rates were found to be approximately 130 pounds/hour versus an allowable rate of about 25 pounds/hour. Gas volumes were determined to be about 35,000 ACFM at a temperature of about 355°. Thus the grain loading measured was about 0.4 grains per ACFM. Orsat analysis indicated 9.5%, CO_2, 10% O_2, 0% CO and 80.5% N_2. Coal analysis indicated the sulfur content to be about 0.6%.[3]

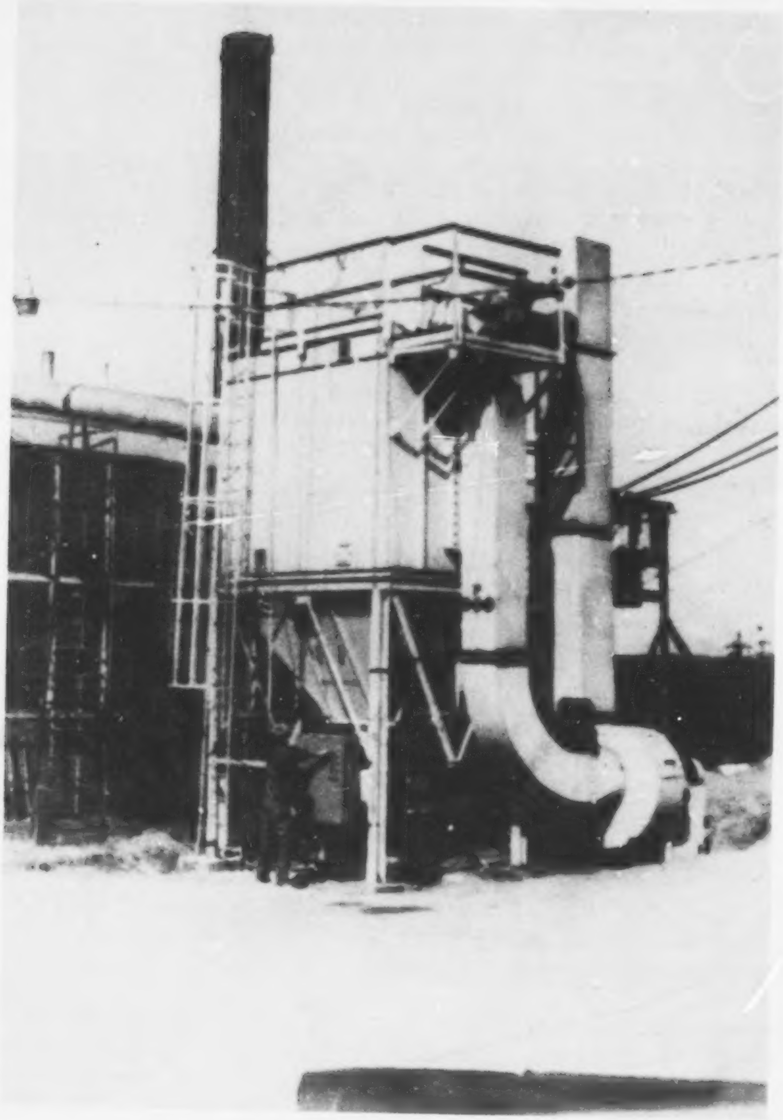


Figure 1

Kerr Pilot Plant

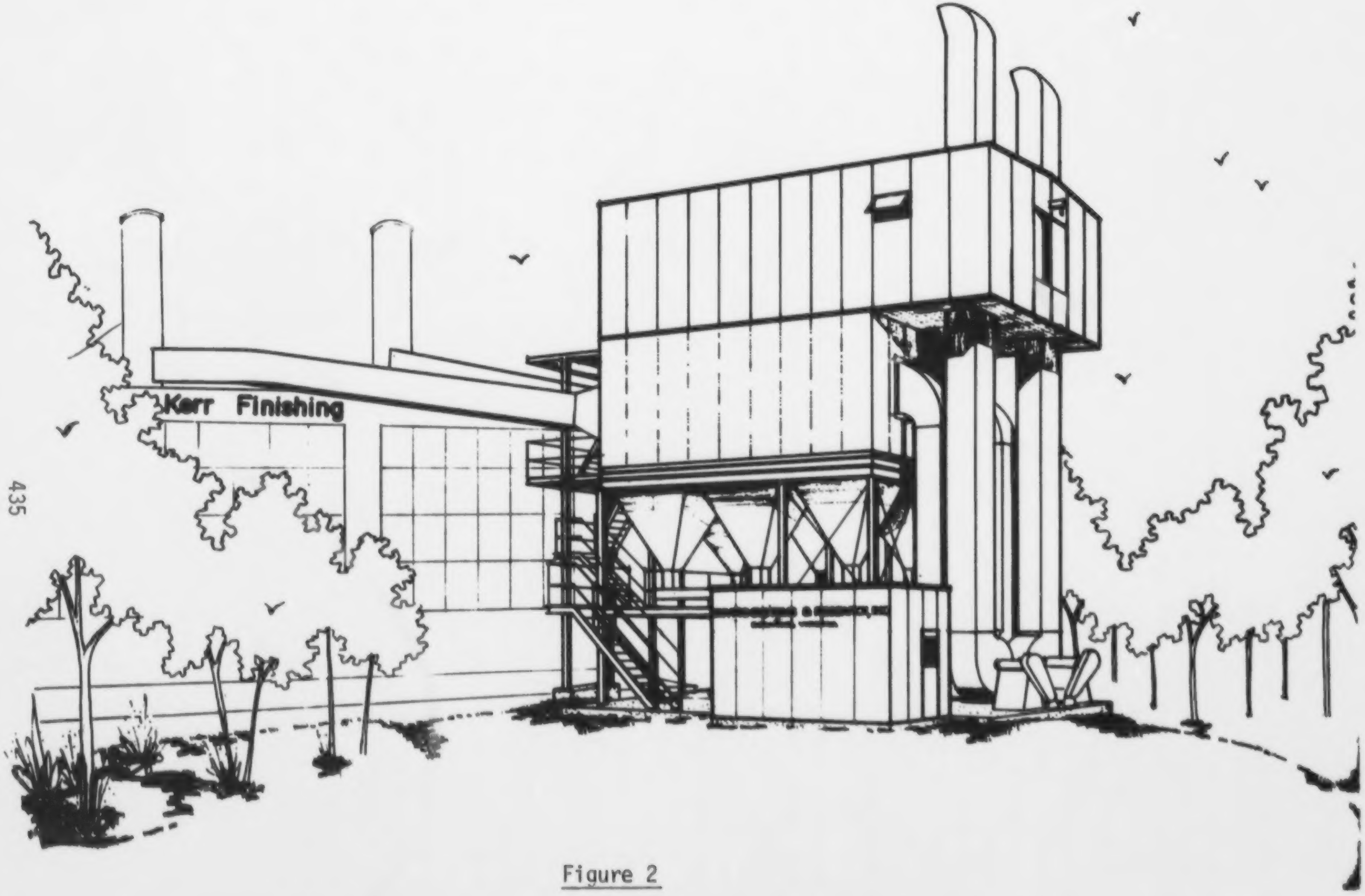


Figure 2

EPA DEMONSTRATION OF THE ENVIRO-SYSTEMS FABRIC FILTER SYSTEM AT KERR FINISHING DIV. FABRICSAMERICA, CONCORD, NORTH CAROLINA

HARDWARE DESCRIPTION

Each boiler is serviced by its own fabric filter system. The heart of each system is the baghouse which is identical in terms of basic hardware. Each baghouse is designed to contain a total of 7,440 square feet of cloth. The house is subdivided into eighteen (18) cells, each cell containing thirty-six (36) bags giving a total house capacity of 648 bags. The bags are 8' - 8" long and 5" in diameter, giving 11.5 square feet of cloth per bag. The bags are hung from the tube sheet, locked in place by two snap rings which are sewn into the bags. The bags are secured to a metal grid at the bottom. A metal cage is set inside the bags to prevent collapse. The baghouses are constructed of 10 gauge mild steel while the hoppers are of 3/16" mild steel plate construction. Both house and hopper are insulated with two (2) inches of fiber board covered with a mild steel skin (Figure 3).

BAGHOUSE OPERATION

The system is brought on line by closing the boiler stack damper and opening the system inlet damper. An auxiliary heater can be employed to preheat the house prior to start-up and it can also be used to purge the house prior to shutdown. The vortex damper is employed to maintain a predetermined pressure at the boiler stack, independent of pressure drop fluctuations through the baghouse system (Figure 4). The operation of the baghouse is as follows: The dirty gases enter one end of the house, pass through the tapered duct into a classifier, then through the bags. The classifier forces the dirty gases to change direction abruptly, forcing the heavier particles directly into the hopper. Dirty gases enter the classifier through a central tapered duct to feed the same quantity of gas into each cell.

The gases are now forced through the fabric, the particulate is deposited on the outside of the bag while the clean gas passes through the center of the bag and into a center exit plenum via an open damper above the tube sheet. The bags are cleaned one cell at a time by closing the cell damper and at the same time introducing clean gas in the reverse direction. The in-rush of cleaning gas expands the bag with a shock causing the "cake" to crack and the particulate falls off the bag into the hopper.

Now that the shock has broken off the outer crust, the flow of clean gas continues pushing and pulling the dust particles away from the fabric in an operation called "drag". This phase of the cleaning has proven significant in minimizing the re-entrainment of fine particles during the cleaning cycle (Figure 5).

The entire operation is monitored and controlled by a console located in the control house. The control panel (Figure 6) is arranged in three sections, with test instrumentation located in the center and baghouse controls at left and right.

General Arrangement **SD-10**

**Not For Construction Purposes*

Pyramid Hopper

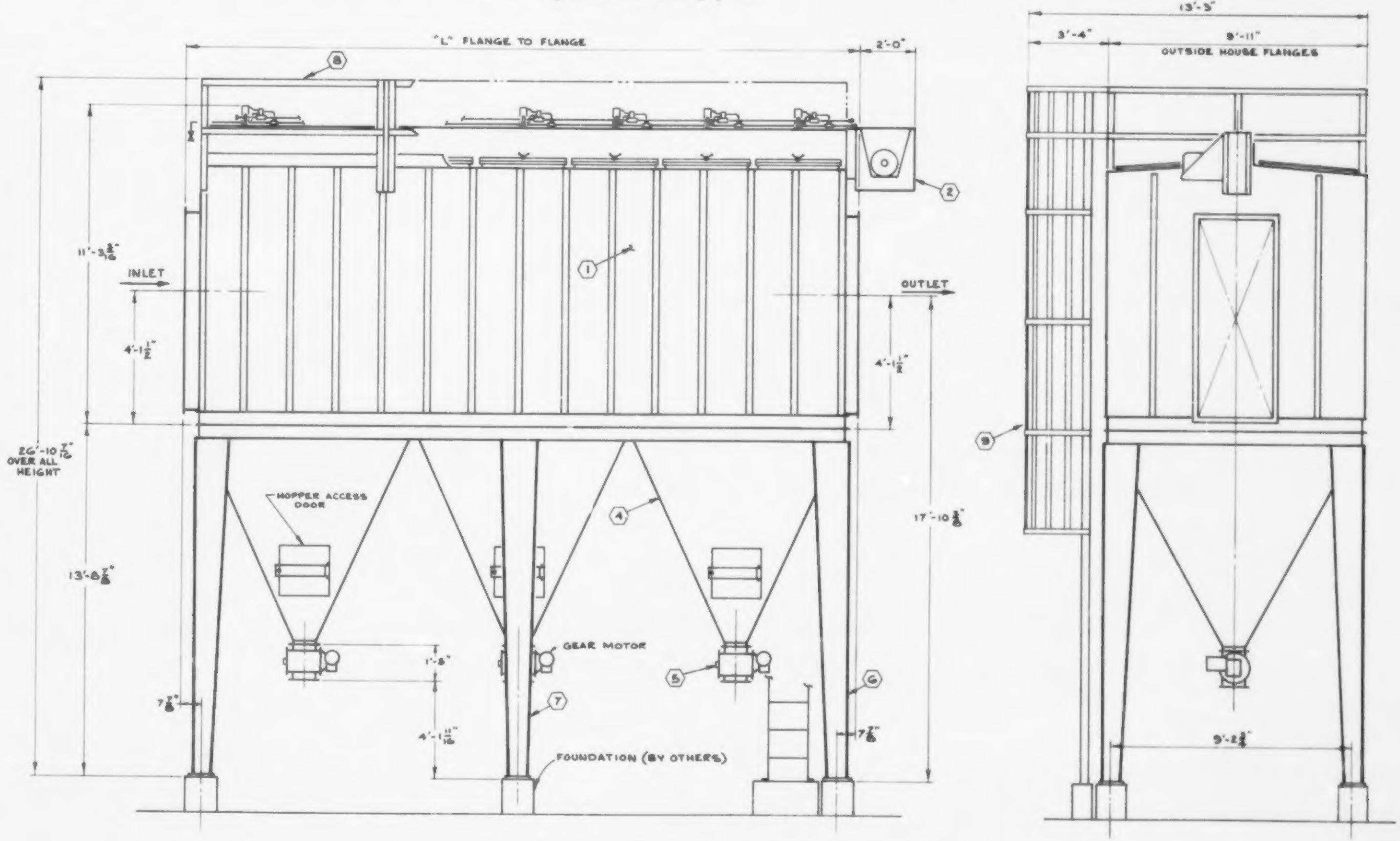


Figure 3

SD General Arrangement with Pyramid Hoppers

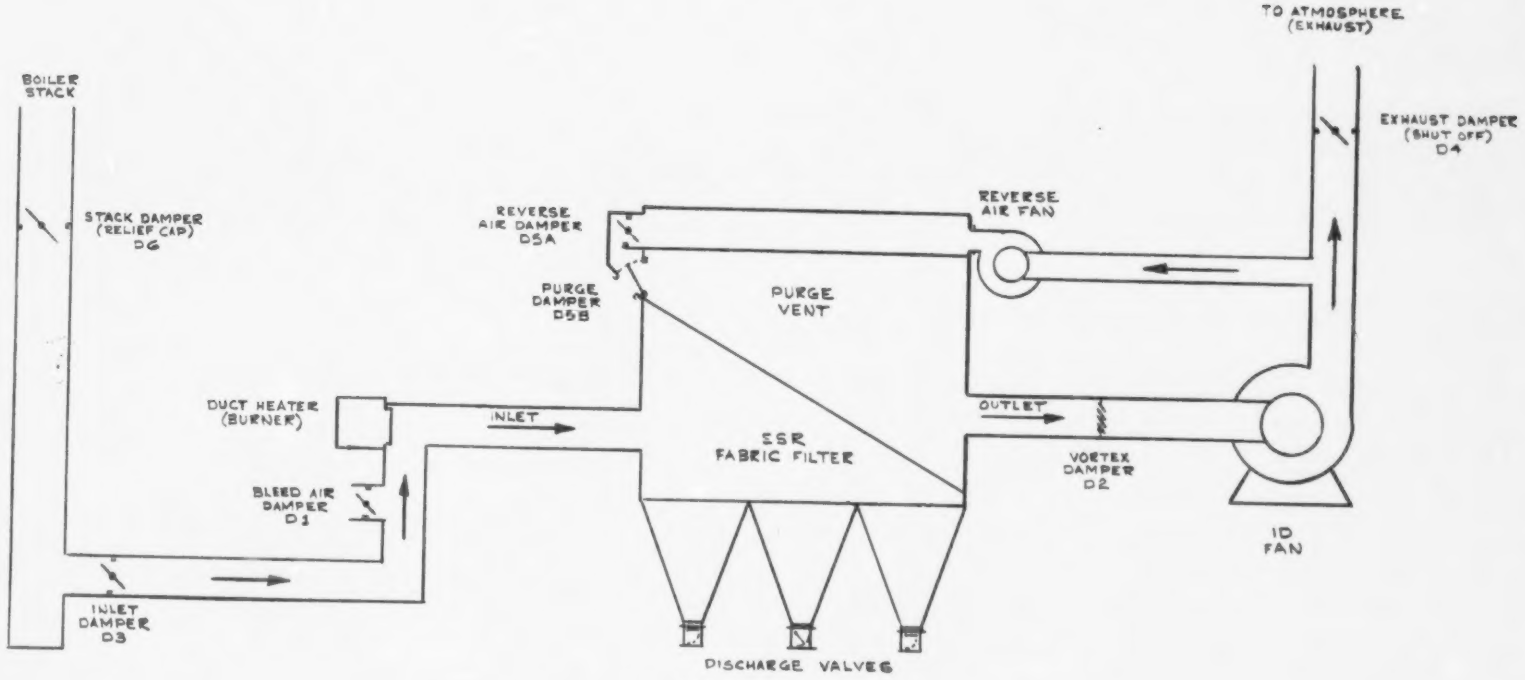
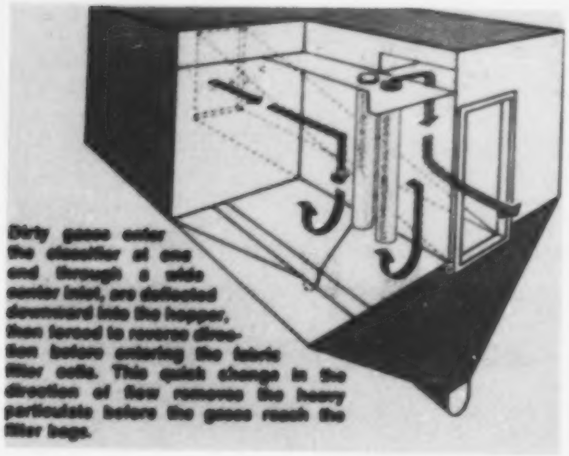


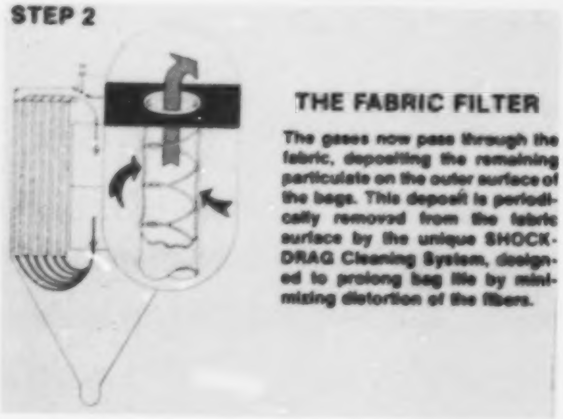
Figure 4

Fabric Filter Schematic


Dirty gases enter the classifier at one end through a wide center inlet, are deflected downward into the hopper, then forced to reverse direction before entering the fabric filter cells. This quick change in the direction of flow removes the heavy particulate before the gases reach the filter bags.

Step 1

Baghouse Pictorial Showing Gas Flow

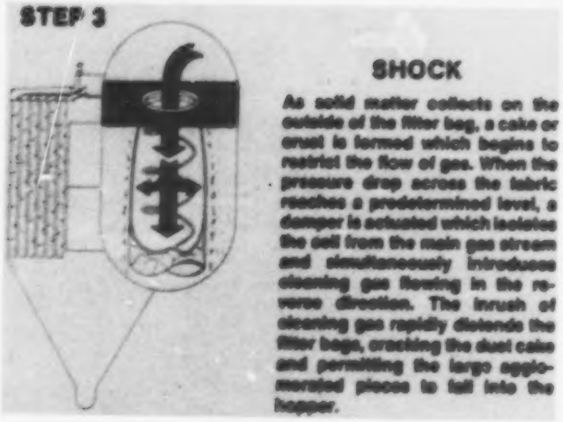


THE FABRIC FILTER

The gases now pass through the fabric, depositing the remaining particulate on the outer surface of the bags. This deposit is periodically removed from the fabric surface by the unique SHOCK-DRAG Cleaning System, designed to prolong bag life by minimizing distortion of the fibers.

Step 2

Baghouse Pictorial Showing Gas Flow

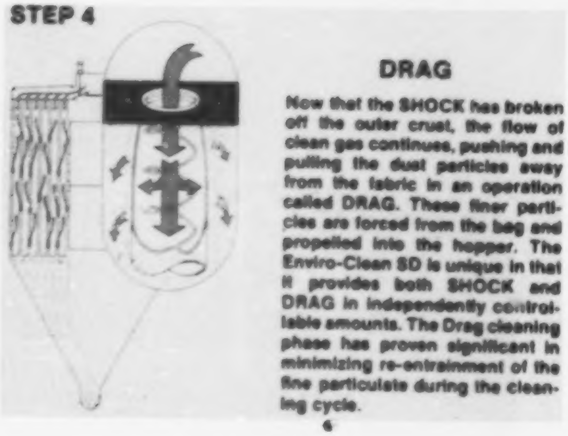


SHOCK

As solid matter collects on the outside of the filter bag, a cake or crust is formed which begins to restrict the flow of gas. When the pressure drop across the fabric reaches a predetermined level, a damper is actuated which isolates the cell from the main gas stream and simultaneously introduces cleaning gas flowing in the reverse direction. The inrush of cleaning gas rapidly distends the filter bags, cracking the dust cake and permitting the large agglomerated pieces to fall into the hopper.

Step 3

Baghouse Pictorial Showing Gas Flow - Shock



DRAG

Now that the SHOCK has broken off the outer crust, the flow of clean gas continues, pushing and pulling the dust particles away from the fabric in an operation called DRAG. These finer particles are forced from the bag and propelled into the hopper. The Enviro-Clean SD is unique in that it provides both SHOCK and DRAG in independently controllable amounts. The Drag cleaning phase has proven significant in minimizing re-entrainment of the fine particulate during the cleaning cycle.

6

Step 4

Baghouse Pictorial Showing Gas Flow - Drag

Figure 5

Reproduced from best available copy.

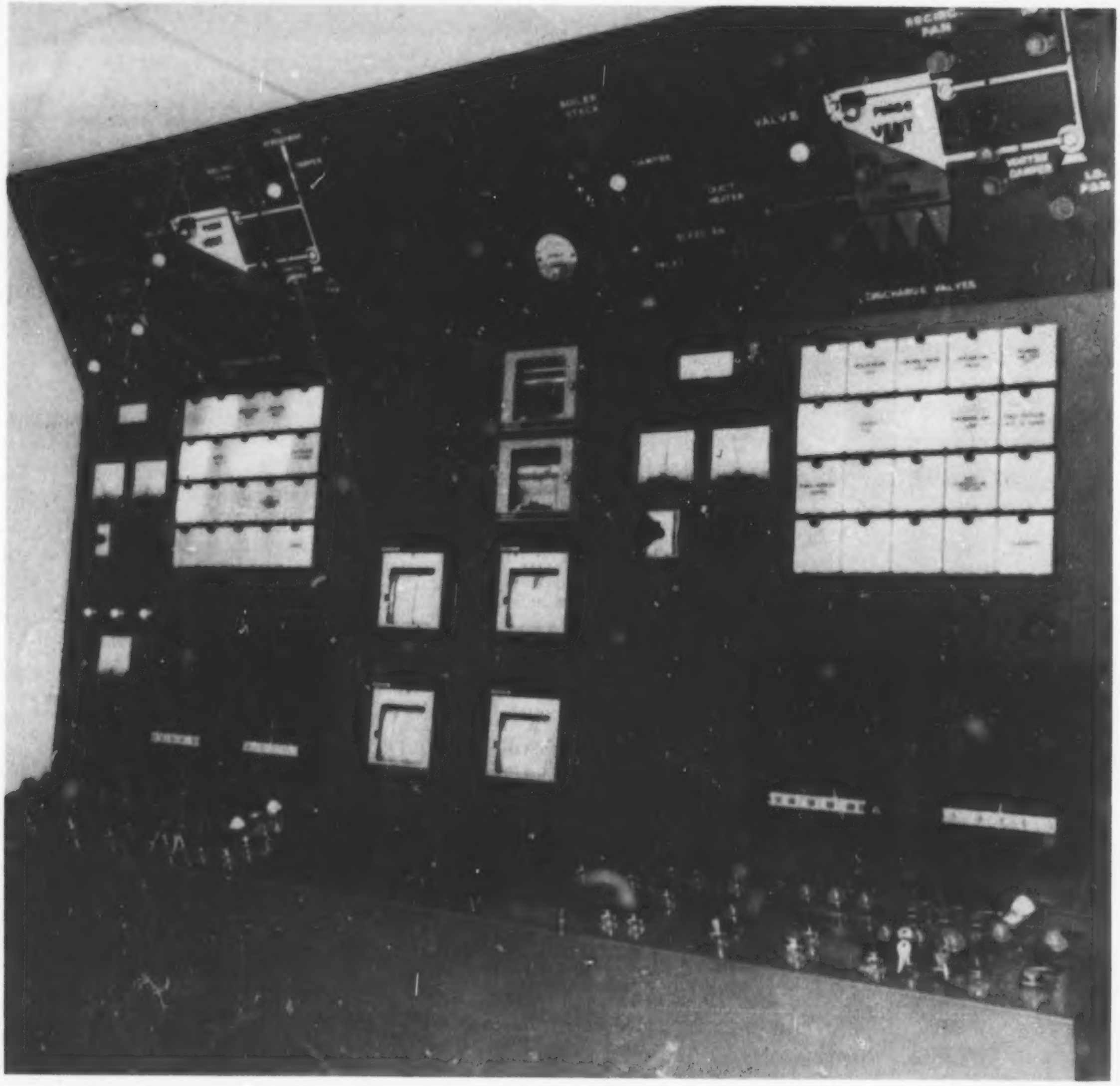


Figure 6

Control Panel

Since the 1976 start-up, several modifications have been made to the system, both to solve unanswered questions as well as to create optimum operating conditions. In order to obtain more effective cleaning of the bags, two different measures were undertaken. On Baghouse No. 2, the original flapper dampers at the top of each cell were replaced by poppet valves. Six months operation indicates that the dampers now seal better and have increased cleaning pressure. In Baghouse No. 1, a pulse-jet system was added to the existing reverse-flush cleaning systems. The combination cleaning system (shock-drag with pulse assist) has proven extremely effective and indications are that the system can clean down even under the most severe conditions.

One other major modification was made to System No. 1. In 1978, a multicyclone was installed after the pre-heater but prior to the baghouse system inlet damper. Particle size data, obtained both before and after installation, show some reduction, after installation, in the concentration of larger particles.

FILTER MEDIA

The fabrics screened in the original pilot program were: Teflon Felt Style 2663 (21-29 oz./yd.^{2}), a tetrafluoroethylene fluorocarbon; Gore-Tex (4-5 oz./yd.^{2}), a microporous Polytetrafluoroethylene (PTFE) membrane on a woven PTFE fabric backing; Dralon-T felt (12-15 oz./yd.^{2}), an Acrylonitrile homopolymer; and Nomex felt, a high temperature resistant nylon fiber (polyamide). Of these media, Teflon felt and Gore-Tex PTFE laminate proved the most promising and were selected as the first to be employed in the demonstration project.

Baghouse No. 1 was outfitted entirely with Teflon felt and in the ensuing twenty-four (24) months of operation has yielded an average replacement rate of 5% per year with no recorded failures during the first year. During this time the house was on-stream five or six days per week with the only significant maintenance being industrial vacuuming of the bags which occurred twice during the first year's operation.

Baghouse No. 2 was started up in 1976 with a complete complement of Gore-Tex bags. One cell (36 bags) was replaced with Huyck glass felt bags in March of 1977 while another cell was outfitted with Globe Albany 22½ oz. woven glass bags in May of 1977. Neither of these last cells has shown failure to date.

Gore-Tex, which had shown a 10% replacement rate after the first year's operation, was completly replaced with 22.5 oz. woven glass bags during the summer of 1978. It is felt that a large number of the Gore-Tex failures can be attributed to manual cleaning and movement of the bags.

Nomex felt and a 15 oz. woven glass bag were also tested in Baghouse No. 2 during 1978. Both were found to be lacking in endurance.

DATA

A profile of the flue gas at the inlet of each baghouse is shown in Table 1.

Characterization of the outlet particle size distribution shows that each of the media tested thus far (Teflon felt, Globe Albany 22.5 oz./yd.^{2} woven glass and Gore-Tex), emits essentially the same range of particle sizes (Table 2 and Figure 7). All comparisons are made at a 6/1 A/C ratio which has been the predominant level of operation at Kerr.

All media tested performed well within the emission boundries set for the Kerr boilers by the State of North Carolina, with the woven glass showing the lowest outlet emissions and Teflon felt the highest (Figure 8).

ECONOMICS

The economics of applying the three media tested to the Kerr boilers were evaluated and compared with those of an electrostatic precipitator.

Installed costs were developed for a fabric filter collector sized to handle 70,000 ACFM at 350° F at air-to-cloth ratios of 3, 6 and 9 to 1. Table 3 shows the influence that the cost of the bags exerts on total installed costs.

Figure 9 shows a comparison of the installed costs for the three bag materials versus the installed costs for an ESP handling the same volume of flue gas but at efficiencies of 95% and 99%. The ESP costs were developed by summing flange-to-flange costs (supplied by an ESP manufacturer) and 70% of the purchase price for erection costs. (This same 70% was used in developing fabric filter erection costs.)

Operating costs were developed for the fabric filters with two, four and six year bag lives and compared with those of the electrostatic precipitator. Fabric filter operating costs were based on actual pressure drops observed at the 6 to 1 air-to-cloth ratio. Precipitator pressure drops were assumed to be 0.5" W.G. Electrical rates are actuals obtained from Kerr. These costs presented in Figure 10 illustrate the importance of achieving longer bag life.

Annualized costs were calculated using the straight line method of depreciation, 6 2/3% per year over 15 years. Other costs called capital charges, which include interest, taxes and insurance, are assumed equal to the amount of depreciation or 6 2/3% of the initial installed costs. Therefore, depreciation plus these other annual charges amount to 13 1/3% of the installed costs. As illustrated in Figure 11, the baghouse employing any of the fabric systems is favorable once a four-year bag life is achieved.

Development of annualized costs employed the formulae published by Edminsten and Bunyard.(4)

Table 1

Inlet Gas Stream Profile

	Inlet to Teflon Felt House	Inlet to Gore-Tex (1977), Then Woven Glass (1978) House
Flue Gas Composition		
CO_2 (%)	4.5	4.4
CO (%)	0	0
O_2 (%)	15.2	14.6
H_2O (%)	5.1	3.1
Temperature (° F)	322	317
Gas Volume (ACFM)	37,700	35,300
Grain Loading (Grains/dscf)	0.5356	0.4272
Inlet Flow Rate (Ft./Sec.)	76.7	61.1
Inlet Opacity (%)	-	40

Table 2

Outlet Characterization by Andersen Impactor
(Particle Sizing)

G/C Ratio 6/1

	Teflon Felt			Woven Glass			Gore-Tex*		
Stage	Diameter,[1] Microns	Loading,[2] Grains/ dscf	Cumulative[3] %	Diameter, Microns	Loading, Grains/ dscf	Cumulative %	Diameter, Microns	Loading, Grains dscf	Cumulative %
1	>11.40	.01503	55.70	>10.89	.00319	51.96	>10.43	.00304	66.41
2	8.00	.00348	45.45	7.64	.00062	42.62	7.32	.00102	55.14
3	4.93	.00326	35.84	4.70	.00057	34.04	4.51	.00116	42.32
4	3.47	.00271	27.85	3.31	.00041	27.86	3.17	.00063	35.36
5	2.26	.00266	20.01	2.15	.00043	21.39	2.06	.00075	27.07
6	1.04	.00230	13.23	.99	.00044	14.76	.95	.00085	17.68
7	.63	.00174	8.10	.59	.00035	9.49	.57	.00069	10.06
8	.46	.00101	5.13	.43	.00036	4.07	.41	.00035	6.19
Back-Up Filter	<.46	.00174	-	<.43	.00027	-	<.41	.00056	-
	Total	.03393		Total	.00664		Total	.00905	

[1] Mean Effective Cut Diameter

[2] Mean Loading Per Stage

[3] Mean Cumulative % Less Than Size Indicated

*No Probe and Nozzle Washes Were Collected

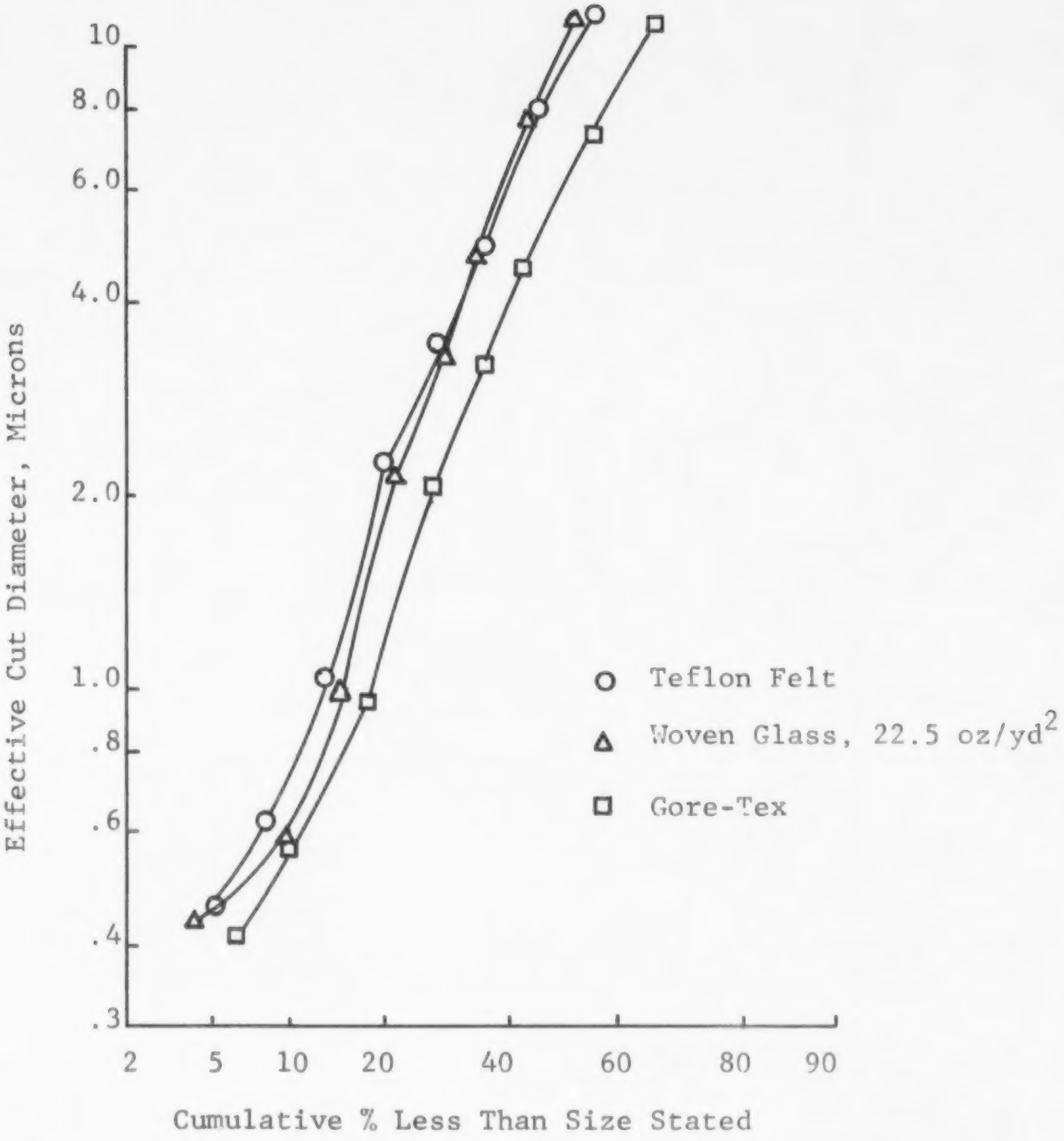


Figure 7

Outlet Particle Size Distribution for Each of Three Filter Media
(G/C Ratio 6/1)

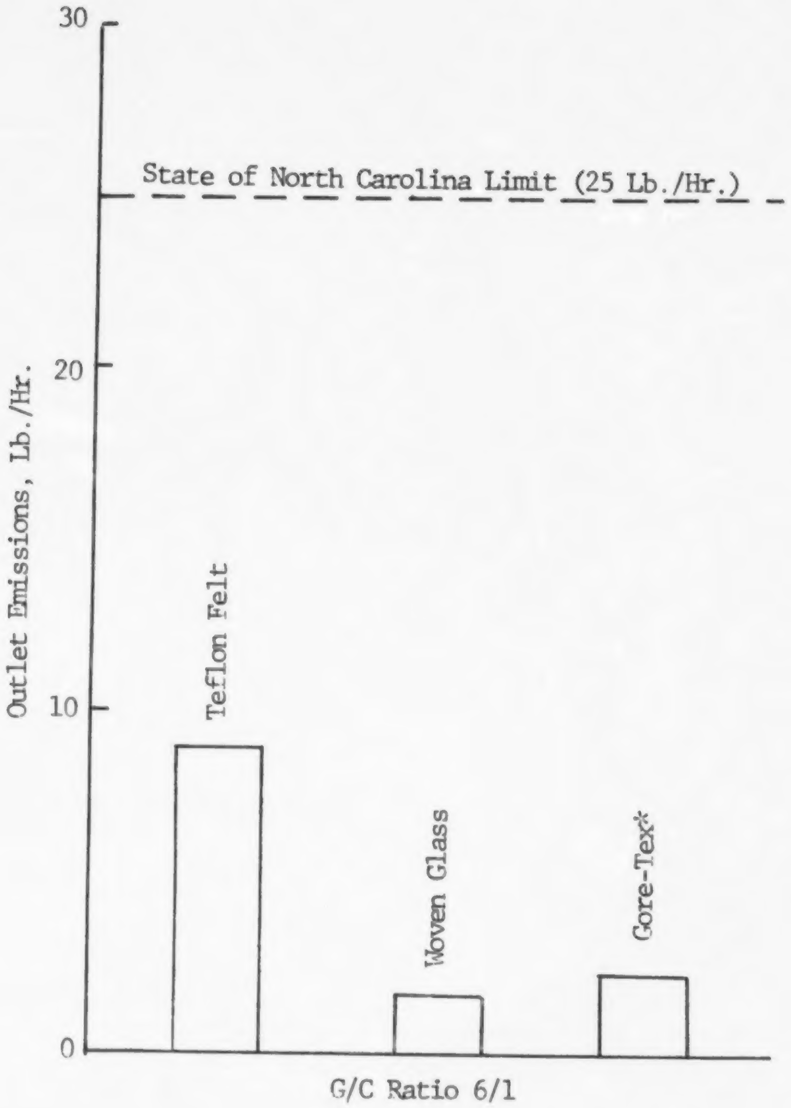


Figure 8

Performance of Three Filter Media in Controlling Emissions from a Coal-Fired Boiler

*No probe and nozzle washes were collected.

Table 3

Bag Cost as a Percentage of Installed Cost

Filter Media	Installed Cost	Bag Cost	Bag Cost as % of Installed Cost
Teflon Felt			
A/C: 3/1	$285,080	$114,480	40.2%
6/1	153,700	57,240	37.2
9/1	120,570	38,160	31.6
Woven Glass			
A/C: 3/1	210,884	40,284	19.1
6/1	116,602	20,142	17.3
9/1	95,838	13,428	14.0
Gore-Tex			
A/C: 3/1	267,800	97,200	36.3
6/1	145,060	48,600	33.5
9/1	114,810	32,400	28.2

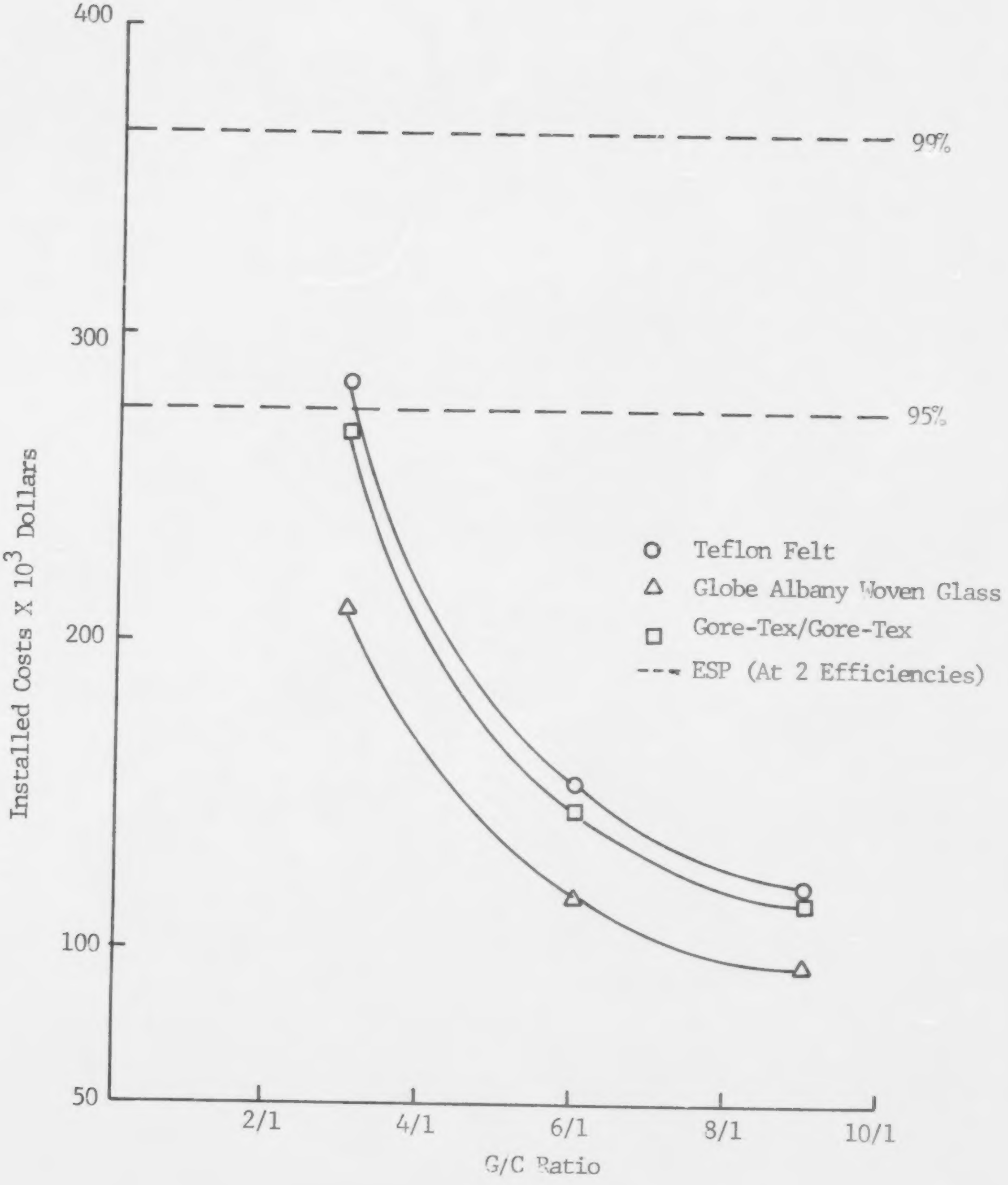


Figure 9

Comparison of Installed Costs for Three Filter Media and Electrostatic Precipitators

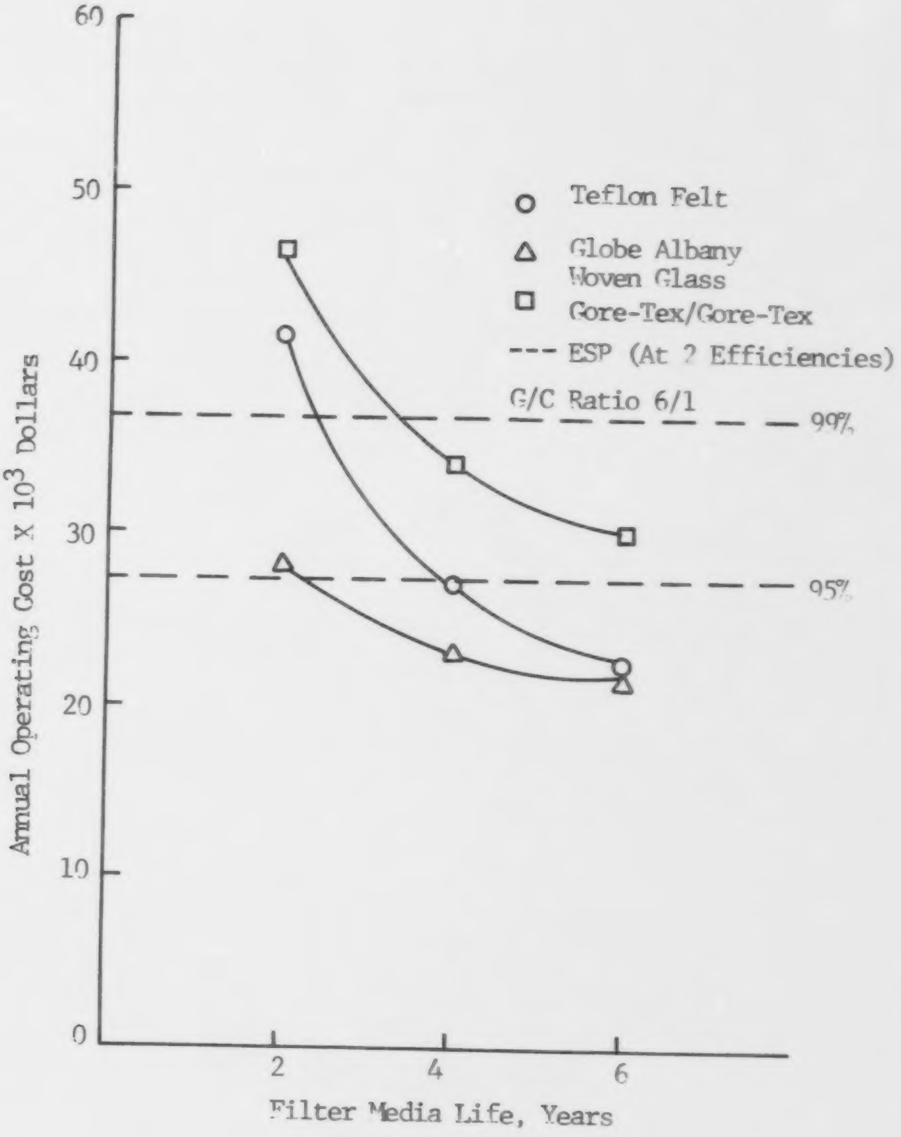


Figure 10

Comparison of Operating Costs for Three Filter Media and Electrostatic Precipitators

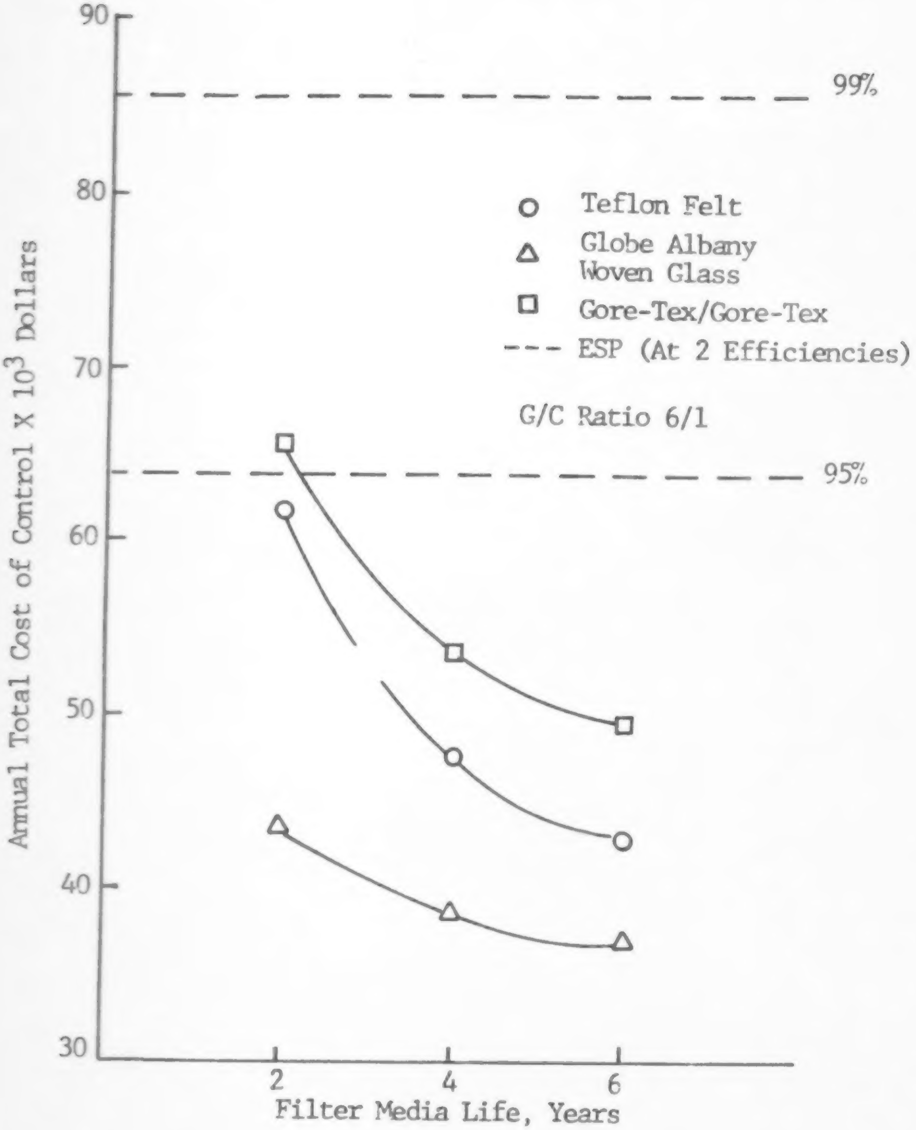


Figure 11

Comparison of Annualized Cost of Control for Three Filter Media and Electrostatic Precipitators

CONCLUSIONS

During the first two years of the full-scale demonstration project, three filter media (Teflon Felt Style 2663, Woven Glass 22.5 Oz./Yd.^{2} and Gore-Tex PTFE Laminate) were evaluated for performance and economy in controlling the fly ash emissions from a stoker boiler. The media all performed well within the particulate emission limits set by the State of North Carolina and each of the media tested emits essentially the same range of particle sizes.

Teflon felt has been operating for better than twenty-four (24) months and appears the most likely candidate to achieve a four-year (and possibly more) bag life.

All of the media studied appear favorable in terms of annualized costs when compared with an electrostatic precipitator at 99% efficiency, once a two-year bag life is achieved.

In January of 1979 a fire of major proportions destroyed the operating facilities at Kerr. The boilers and baghouses, although unharmed, have not operated since. Present plans call for the relocation of the baghouses to a recently acquired Kerr facility in Travelers Rest, South Carolina.

It is anticipated that the test program will start again in the fall of 1979 at its new location.

REFERENCES

[1] McKenna, J. D., "Applying Fabric Filtration to Coal-Fired Industrial Boilers: A Preliminary Pilot Scale Investigation". EPA 650/2-74-058, July, 1974.

[2] McKenna, J. D., Mycock, J. C. and Lipscomb, W. O., "Applying Fabric Filtration to Coal-Fired Industrial Boilers: A Pilot Scale Investigation". NTIS PB-245-186, August, 1975.

[3] McKenna, J. D. and Brandt, K. D., "Demonstration of a High Velocity Fabric Filtration System Used to Control Fly Ash Emissions". Presented at the Third Symposium of Fabric Filters for Particle Collection, Tucson, Arizona, December 5-6, 1977.

[4] Edminsten, N. G. and Bunyard, F. L., "A Systematic Procedure for Determining the Cost of Controlling Particulate Emissions from Industrial Sources". Journal of the Air Pollution Control Association, V20, N7, p. 446 (1970).

ACKNOWLEDGEMENTS

This program was sponsored by the Federal Environmental Protection Agency with participation by Kerr Industries and Enviro-Systems & Research, Inc.

EPA MOBILE FABRIC FILTER - PILOT INVESTIGATION OF HARRINGTON STATION PRESSURE DROP DIFFICULTIES

by

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ABSTRACT

This report describes the Environmental Protection Agency mobile fabric filtration performance evaluation at Harrington Station, Amarillo, Texas. The primary objective was to evaluate several bag candidates for new and retrofit application for the full-scale baghouse systems. A secondary objective was to evaluate operating and cleaning parameters. The purpose was to assess alternate means for reducing high pressure drop levels currently being experienced at Harrington Station. The mobile facility was operated in a representative manner with the full-scale baghouse for candidate bag evaluation. Appropriate changes in cleaning parameters showed reduction in pressure drop levels, as did alternate bag types. Results from electrostatic measurements indicated that significant charging levels exist. Performance results from the mobile baghouse are discussed and related to the full-scale system.

INTRODUCTION AND OBJECTIVE

This pilot-scale fabric filter is one of three conventional particulate emission control devices mobilized by the Particulate Technology Branch, Utilities and Industrial Power Division, Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency (PATB/UIPD/IERL/EPA), Research Triangle Park, North Carolina. The objective is to evaluate and compare the performance characteristics of a pilot-scale baghouse, electrostatic precipitator (ESP), and scrubber on industrial particulate emission sources. The purpose is to provide characteristic information and insight for appropriate selection of particulate control devices, in light of operation, performance, and cost considerations.

The Harrington Station Unit No. 2 fabric filter system, belonging to Southwestern Public Service Company (SPS Co.), was of interest to IERL/EPA prior to its startup in June 1978. Among other evaluations, IERL had directed a performance evaluation to be conducted with its mobile baghouse system on Unit No. 1 during the spring of 1977.[1] One of the bag/cleaning cases studied during this evaluation was representative of the Unit No. 2 baghouse system. Data from this representative case were integrated into the baghouse performance model by GCA Corporation.[2] The model predicted that operating pressure drop levels would be significantly higher than the design levels. As predicted, the operating pressure drop level currently being experienced is significantly higher than the design level. In light of these circumstances, SPS Co. and IERL have cooperatively entered into an investigation to be conducted with the EPA mobile baghouse to assess pressure drop remedies. Acurex performed and conducted this investigation by evaluating several bag candidates and other pertinent pressure drop parameters.

This report summarizes the results of the second EPA mobile baghouse performance evaluation at Harrington Station during the spring of 1979. The mobile baghouse treated a slipstream from Unit No. 1 educted upstream from the pollution control system. The conditions of the slipstream and the pilot baghouse were representative of the Unit No. 2 flue stream and baghouse system, respectively. Boiler and pilot baghouse operating data were collected on a regular basis. Particulate concentration and size distribution measurements were conducted on the influent and effluent streams. Several glass fiber bag types were methodically evaluated, with emphasis on pressure drop performance and characterization. Performance levels and trends are included in this report, along with analytical discussions on operating and particulate data, coal type, and means of data reduction and interpretation.

CONCLUSIONS

- Acid-Flex fabric had the best operating performance characteristics of the candidate bags evaluated.
- The Teflon B fabrics and the silicone-graphite fabric had comparable performance characteristics.
- Increasing shake frequency resulted in dramatic improvements in cleandown for all fabric types.
- Increasing deflation pressure resulted in significant improvement in cleandown for all fabrics.
- Silicone-graphite bags had slightly higher emission levels than the other bag types.
- Cage voltage measurements indicated that sufficient electrostatic levels are present to have a potential effect on cleandown and porosity.
- The Wyoming/New Mexico coal blend appeared to generate a dust cake with slightly better cleandown characteristics.

DESCRIPTION OF FACILITIES

Test Site

Harrington Station is owned and operated by Southwestern Public Service Company. It consists of two 350 MWe pulverized coal (PC)-fired boilers. The identical boilers were completed from 1976 to 1978 and represent current design and operating methodology. Emissions are controlled by a series combination ESP/marble-bed wet scrubber on Unit No. 1, and by a baghouse with silicone-graphite coated glass bags on Unit No. 2. A third unit, now under construction, will employ a baghouse. Bag selection for Unit 3 has not been finalized.

Harrington Station generally burns a low sulfur coal from Gillette, Wyoming. Due to limited availability of Wyoming coal, a New Mexico type was fired to supplement coal reserves. Site characterization data for the Harrington Station boiler, flue gas and coals are presented in Tables 1 and 2.

Full-Scale Baghouse

The emissions from Unit No. 2 are controlled by a fabric filter, consisting of two houses designated East and West, each with 14 compartments. Detailed design and operating specifications are given in Table 3.[3] In March 1979, after 6 to 8 months of on-stream time, the operating pressure drop ranged from 9 to 11 inches W.C. at full load and SPS Co. projected additional bag life to be a maximum of 6 months.

Pilot Baghouse

The EPA mobile baghouse consists of a single compartment containing three 14.1 cm (5 9/16 in.) diameter by 1.83 m (6 ft.) long bags. Designed for the purpose of determining the effects of dust properties, fabric media, cleaning parameters and other operating parameters on fabric filter performance, the system has the following capabilities:

- Filtration at cloth velocities as high as 6 m/min with a pressure differential up to 50 cm of water and at gas temperatures up to 260°C.
- Adaptability of mobile system to cleaning by mechanical shake, pulse jet, or low pressure reverse flow with cleaning parameters varying over a wide range.
- Continuous 24-hour operation with use of automatic instruments and controls.

The mobile fabric filter is housed in a 2.4 m by 12 m tandem-axle trailer. A more complete description of the EPA mobile baghouse is presented in Reference 4.

PROGRAM METHODOLOGY

Installation

The mobile baghouse was located adjacent to and then slipstreamed from Unit 1. The slipstream probe was installed in the ductwork downstream of the air preheater and upstream of the pollution control devices. The slipstream was withdrawn and isothermally transported to the pilot unit at velocities somewhat less than plant conditions. A return line from the pilot baghouse back to the site inlet duct was employed due

TABLE 1. HARRINGTON STATION
COAL ANALYSIS* SUMMARY

	Black Thunder Mine Campbell County, Wyoming		McKinley Mine Gallup, New Mexico	
	Typical	Range	Typical	Range
Moisture	28.4	24.2 - 34.4		14.0 - 15.5
Ash	4.8	3.3 - 6.7		11.5 - 13.5
Volatile	31.9	27.4 - 38.0		
Fixed Carbon	35.0	31.0 - 40.0		
	100%			
MJ/kg	20.0	18.3 - 21.3		23.2 - 24.8
Sulfur Content	0.33	0.09 - 0.51		.33 - .40

*all analyses as received

TABLE 2. BOILER AND FLUE GAS CHARACTERISTICS[7]

Boiler Type	Pulverized Coal (PC)
Generation Capacity	350 MW
Coal Type	Low Sulfur Low Ash Wyoming Low Sulfur High Ash New Mexico/ Wyoming Blend
Flue Gas Flow Rate	34000 acm/min
Gas Velocity	24 - 30 m/sec (78.7 - 98.4 ft/sec)
Temperature	125 - 185°C (257 - 365°F)
Particulate Loading	2.4 - 3.4 gm/DNCM (1.05 - 1.5 gn/DSCF)
CO_2	12.3%
O_2	5.0%
N_2	77.0%
H_2O	5.7%

TABLE 3. DESIGN AND OPERATING SPECIFICATIONS FOR HARRINGTON UNIT NO. 2, BAGHOUSE [3,8]

Design	Metric	English
Gas temperature	156°C	313°F
Gas Flow Rate	4.67×10^4 acmn	1.65×10^6 acfm
A/C Ratio	1 m/sec	3.27 ft/sec
Bag type	Silicone/Graphite coated glass fiber	
Compartments	28	
Bags/Compartments	204	
Bag Design	Caps with Eye Bolts	
Bag Dimensions	0.29 x 9.3 m	11.5" x 30.5'
Number of Bags	5712	
Total Cloth Area	4.78×10^4 m^2	5.14×10^5 ft^2
Cleaning Mode	Deflate/Shake	
Cleaning Parameters		
Acceleration	1.56 g (15.3 m/sec^2)	1.56 g (50.2 ft/sec^2)
Amplitude	3.8 cm	1.5 in.
Frequency	3.2 cps/sec	
Duration	23 sec	
Reverse Air ΔP W. C.	0 - 0.5 in.	0 - 1.27 cm
Operating		
Bag Pressure Drop	15 - 28 cm	6 - 11 in.
Gas Temperature	127 - 188°C	260 - 370°F
Gas Flow Rate	$2.8 - 4.0 \times 10^4$ acmn	$1.0 - 1.4 \times 10^6$ acfm
A/C Ratio	0.9 - 1.2 m/sec	3.0 - 4.0 ft/sec

to high negative static pressure in the plant duct and limited blower capacity in the pilot baghouse. The slipstream was heated and insulated while the return line was insulated only. Inspection of the ducting after testing indicated marginal dropout of particulate, due to either gravitational or centrifugal forces.

Operation

The pilot baghouse was operated and tested continuously in weekly increments of 4 to 5 days. Normal baghouse startup and operating procedures were employed and included a preheat procedure to avoid the acid dew point. Candidate bags were installed in a methodical manner and were conditioned for 24 hours prior to any performance testing. Bag test periods ranged from 1 to 8 days, depending on performance and interest levels.

Candidate Bags

The candidate bags for this program included the following:

- W.W. Criswell silicone-graphite coated fiber glass, style 445-04 (same bag installed in Harrington Unit 2 baghouse).
- W.W. Criswell Teflon B coated fiber glass, style 442-570C2.
- Menardi-Southern Teflon B coated fiber glass, style MS-601.
- Fabric Filter Acid-Flex fiber glass, style 504-1.
- Fabric Filter all filament fiber glass, style 50G-ITC.
- Fabric Filter Goretex laminate fiber glass.
- Menardi-Southern Teflon B coated fiber glass, reverse-air bags with spreader rings.

Due to performance and/or interest level, the last three bags were not tested for a sufficient length of time to generate meaningful data and are not included in further discussions. A summary of bag specifications for the other four candidate bags is given in Table 4.

Test Conditions

The mobile baghouse was operated at relatively constant temperature and air/cloth levels. Cleaning conditions for each bag type were initially set to be consistent with cleaning conditions for the full-scale unit. Discretionary modifications of pertinent cleaning parameters were made to assess alternate means of pressure drop reduction other than and in relation to bag type. Further clarification of bag cleaning rationale will be discussed later. A summary of the operating conditions, cleaning parameters and cleaning modes is presented in Table 5.

TABLE 4. COMPARISON OF BAG SPECIFICATIONS

	Fabric Filter Acid Flex Style 504-1	W. W. Criswell Teflon B Style 442-57DC2	W. W. Criswell Silicone/Graphite Style 445-04	Menardi-Southern Teflon B Style MS-601
Fabric	woven glass	woven glass	woven glass	woven glass
Weight Oz./yd^2	9.8	10.5	11.0	9.5
Weave	3x1 twill (left hand)	3x1 twill (right hand)	3x1 twill (right hand)	3x1 twill
Thread Count	54x30	54x30	65x33	54x30
Permeability cfm/ft^2@.5 in. H_2O	45-60	60-80	45-65	75
Finish	4.0 - 4.5% multi-component proprietary finish graphite/silicone/teflon/x base + teflon B coating	Teflon B 10% by wt.	silicone & graphite 1% by wt. total	Teflon B 10% by wt.
Warp Yarn	75 1/0	150 1/2	150 1/2	150 1/2
Fill Yarn	50 1/0 text. } 2 ply 150 1/0	150 1/4 all textured	37/S textured	150 1/4 all textured (turned inside)

TABLE 5. SUMMARY OF OPERATING CONDITIONS FOR PILOT BAGHOUSE

Flue Gas Flow Rate	2.3 - 2.5 acm/min (80 - 90 acfm)
Temperature	130 - 190°C (266 - 374°F)
Bag Terminal Pressure Drop	15, 20, 25, cm W. C. (6, 8, 10, in. W. C.)
Air/Cloth Ratio	0.95 - 1.07 m/min (3.1 - 3.5 ft/min)

CLEANING CHARACTERISTICS

Shake Parameters	
Amplitude	0.95 cm (.375 in.)
Frequency	3.2 and 6.4 cycles per second
First Delay	30 seconds
Shake Duration	10 seconds
Final Delay	60 seconds
Acceleration	0.39 g (3.8 m/sec^2) at 3.2 cps 1.56 g (15.2 m/sec^2) at 6.4 cps
Bag Tension	13.6 kg (30 lbs)
Deflation Parameter	
Reverse ΔP	1.2, 12 cm (0.5, 5.0 in.)

CLEANING MODES	SYMBOL
[a]Low Deflation - Low Shake Frequency (LD-LSF)	A
[b]High Deflation - Low Shake Frequency (HD-LSF)	B
Low Deflation - High Shake Frequency (LD-HSF)	C
High Deflation - High Shake Frequency (HD-HSF)	D

a. Low Deflation : 1.2 cm reverse air pressure drop (corresponds to reverse flow air-to-cloth ratio of approximately 1.7

b. High Deflation : 12 cm reverse air pressure drop (corresponds to reverse flow 3 to 4 times that for low deflation

Two coal types were fired in Unit No. 1 during the evaluation period with a two- to threefold difference in ash content between the coal types. Previous experience with the high-ash New Mexico coal showed higher concentration and bag pressure drop on the full-scale baghouse. Despite the known performance sensitivity to coal type, accountability of coal type usage was indefinite during segments of this study.

Data Acquisition

The following pilot baghouse data were recorded continuously throughout the program:

- Pressure drop across the bags
- Gas flow rate pressure drop across a Stairmand disc

Other pilot baghouse data were manually recorded semihourly:

- Temperature profile across the system
- Static pressure profile across the sytem
- Slipstream interface temperature
- Cleaning cycle data (ΔP_R, ΔP_T, flow ΔP, shakes/cycle, etc.)

Pertinent boiler operating data were recorded hourly in the control room, and copies of the logs were made available for the test period. Coal samples were taken 3 times a day, and results of coal analyses were also made available.

Flue gas composition and velocity data were taken at least once per shift for methodology-assurance and particulate sampling preparation.

Particulate Measurements

Total mass and impactor measurements at the inlet and outlet locations were conducted at isokinetic conditions. Brink and Andersen impactors measured the inlet and outlet size distributions, respectively. All filters and substrates were made of Reeve Angel 934 AH material because of low sulfur dioxide (SO_2) absorptivity. All substrates were preconditioned for 6 hours. Samples were obtained with extractive probes fitted with interchangeable nozzles at average velocity locations. Sampling trains similar to that described in Method 5 of the FEDERAL REGISTER were used.

Data Reduction

Several analytical tools were employed in the reduction and analysis of bag pressure drop, particulate concentration and size distribution data. The large number of tests taken over a variety of conditions for the program duration required a substantial analytical effort.

A computer program was used to calculate impactor stage cut-points and dust loadings. Fractional penetrations were calculated using a program that performs the following:[5]

- Log-normal transformation of inlet and outlet cumulative size distributions
- Linear, quadratic, and spline fits to the transformed data
- Analytical differentiation of the fitted curve
- Calculation of fractional penetrations from differential inlet and outlet size distributions

Operating performance was evaluated primarily with respect to fabric/cake drag and cleandown levels. Fabric/cake drag, known as specific cake resistance coefficient (K_2), was estimated by a methodical approach. Cleandown levels were determined by records of residual drag. The fundamentals of baghouse performance modeling were utilized to eliminate fluctuations in particulate concentration and filtration velocity.

Since it was impractical to measure cake mass for all the candidate bags, values of K_2 were determined on the basis of dust concentration instead. Values of estimated K_2 were calculated by the following relationship:

$$K_2 = \frac{(\Delta P_T - \Delta P_R)}{V^2 C t}$$

where:

ΔP_T =	Terminal Drag	N/m^2
ΔP_R =	Residual Drag	N/m^2
V =	Filtration velocity	m/min
C =	Dust concentration	g/m^3
t =	Filtration time	min

Prior to averaging K_2 values, they were arranged in chronological order and the transient values (corresponding to bag conditioning) were eliminated. Since the pressure drop-time profiles showed a linear relationship, the mean pressure drop is the average of residual and terminal values. This approach provided a fundamental basis for comparing bag types and cleaning conditions.

RESULTS AND DISCUSSION

This program was directed to assess alternate means for reducing high pressure drop levels that were being experienced at Harrington Station. Factors contributing to high pressure drop levels were bag type, cleaning parameters, and air-to-cloth ratio. Available means of reduction were appropriate selection of bag type and cleaning conditions. Optimization of these means is recommended, since their synergistic effects can be substantial.

SUMMARY OF OPERATING PERFORMANCE

A summary-level accounting for this evaluation is presented and displayed in Table 6 and Figure 1, respectively. The residual bag pressure drop values in Table 6 and the curves for average pressure drop vs. filtration time allow a ranking of candidate bags and an assessment of cleaning conditions. The results from the analytical and graphic treatment clearly show the Acid-Flex bags to exhibit the lowest pressure drop performance. The Acid-Flex bags achieved both the lowest residual pressure drop and lowest specific cake resistance coefficient values consistently for all cleaning conditions. The other three bag types performed to a lesser degree with essentially comparable operating characteristics.

Results from bag cleaning characterization show that higher cleaning energy also reduces operating pressure drop levels. Enhancement of deflation and/or shake cleaning levels consistently achieved lower residual and mean pressure drops. Increasing shake frequency is a more effective and available means for pressure drop reduction.

Estimated K_2 Results

Specific cake resistance is the effective porosity indicator relating fabric cake drag to operating conditions. By the straightforward approach discussed earlier, a realistic porosity or drag indicator can be derived directly from the operating data. The estimated K_2 values represent the effective fabric/cake porosity.

Compilation of estimated K_2 values is presented in Table 6 for each bag and cleaning mode. The first column of estimated K_2 values represents the test conditions, while the values in the second column are for standard conditions as defined in the GCA performance model. These results consistently demonstrate that the effective porosity of the dust cake on the Acid-Flex bags was significantly lower than that for the other candidate bags.

TABLE 6. PILOT BAGHOUSE RESIDUAL PRESSURE DROPS AND SPECIFIC CAKE RESISTANCE CO-EFFICIENTS

Bag Type	ΔP_T CM	ΔP_R CM Cleaning Mode				K_2 $\frac{N\text{-Min}}{g\text{-m}}$	
		$A^{\dagger}$	$B^{\dagger}$	$C^{\dagger}$	$D^{\dagger}$	Actual 160°C 1m/min	Stg. 25°C 0.61m/min
Acid Flex	15	8.9	4.8	3.6	-	10.4	6.2
	20	9.7	6.1	4.1	-		
	25	10.2	6.6	-	-		
Minardi Southern Teflon B	15	10.7	7.6	9.7	6.1	20.4	12.2
	20	12.9	8.6	-	6.1		
	25	-	8.4	-	-		
Criswell Teflon B	15	12.7	8.9	-	-	15.7	9.4
	20	14.0	10.2	-	-		
	25	-	-	-	-		
Criswell Graphite/Silicone	15	11.4	*5.6	-	-	13.0	7.8
	20	14.0	*6.6	-	-	11.6	7.0
	25	-	*7.1	-	-		

*Wyoming : New Mexico Coal 1:1 Blend
All others Wyoming Coal

† See Table 5 for key.

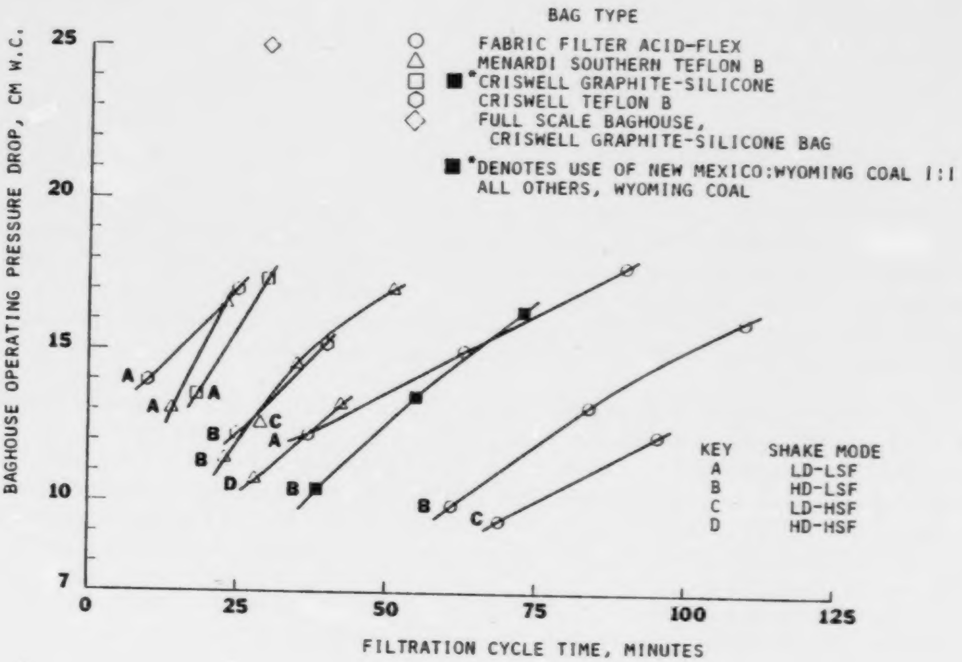

Figure 1. Baghouse operating pressure drop versus filtration cycle time.

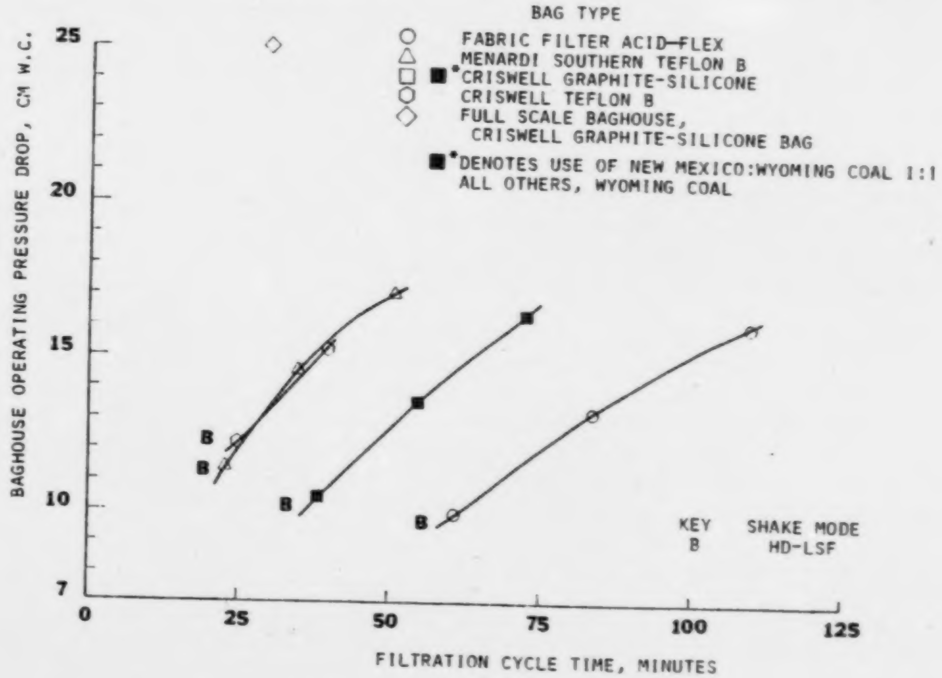

Figure 2. Comparison of performance characteristics of candidate bags.

Effect of Cleaning Conditions

The factors which ultimately define the degree of cleandown are those which determine the type and degree of cleaning energy delivered to the bags for dislodgement of the dust cake. The fabric must be flexed in some manner and to a degree sufficient to break the dust cake. This flexure overcomes the adhesive forces between particles within the dust cake and/or those between the particles and the fabric.

Discussions with representatives of the utility and baghouse vendor led to the conclusion that the shake cleaning cycle in the pilot baghouse could not duplicate that in the full-scale house. This conclusion was based on differences in amplitude and harmonic shaker motion and bag size (e.g., aspect ratio). Consequently, the cleaning parameters were varied with respect to deflation pressure, shake frequency, and shake duration to determine if any one of the bag candidates would perform in a superior fashion over the range of cleaning modes. Cleaning was initiated at the terminal levels of 15, 20, and 25 cm W.C.

The difference in the cleandown characteristics for the four fabrics is shown in Table 6. In mode A, when cleaning was initiated at a terminal pressure drop, ΔP_T, of 15 cm W.C., the resulting residual pressure drop, ΔP_R, is lowest for the Acid-Flex fabric. This differential becomes even more significant as the ΔP_T increases. At a ΔP_T of 25 cm W.C., the Acid-Flex still had a lower ΔP_R than the other three fabrics at a ΔP_T of 15 cm.

The greatest differential in ΔP_R levels was realized between low and high shake frequency (modes A and C). The Acid-Flex responded to a higher degree, 140-150 percent improved cleandown, than did the silicone/graphite bag, 100-115 percent, while the Teflon B fabric showed minimal improvement in the range of only 10 percent.

Significant improvement in cleandown was also realized when going from low to high deflation pressure (modes A and B). However, this would not be a practical change in the Harrington cleaning cycle since experience has already shown that operation at design deflation pressure of 1.3 cm (0.5 in W.C.) causes the bags to pancake and prevents dust cake removal during the shake cycle. However, it does focus interest on a combination reverse air/shake cleaning cycle with ring bags.

The curves displayed in Figures 2 and 3, which are the average pilot baghouse ΔP vs. filtration time for modes A and B, again show Acid-Flex to be the most attractive fabric, with the other three fabrics exhibiting essentially comparable levels of performance. These curves reflect the effect of the K_2 values for each bag type since they determine the filtration time required to reach a predetermined ΔP_T.

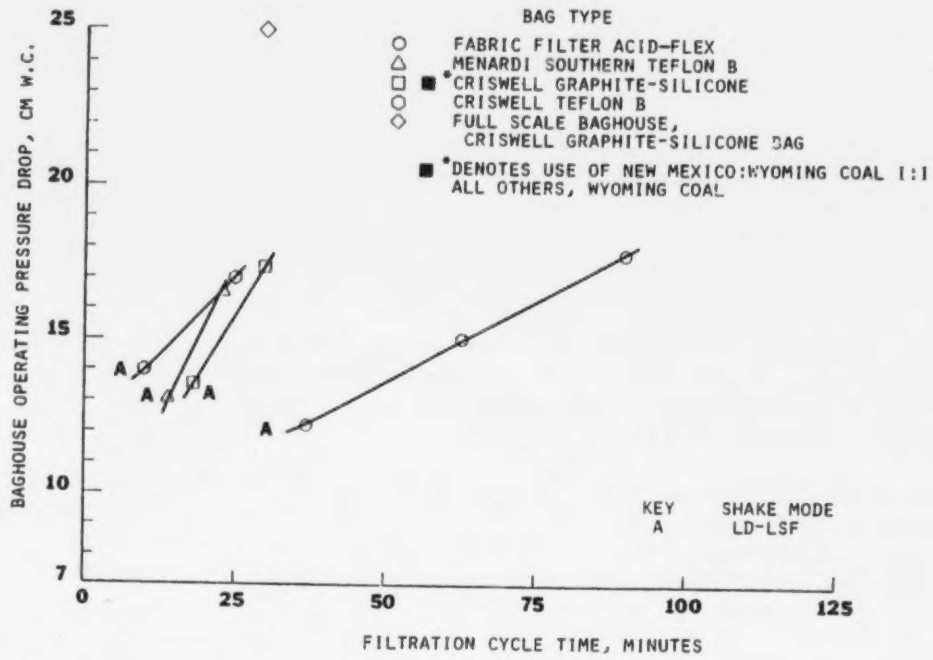

Figure 3. Comparison of performance characteristics of candidate bags.

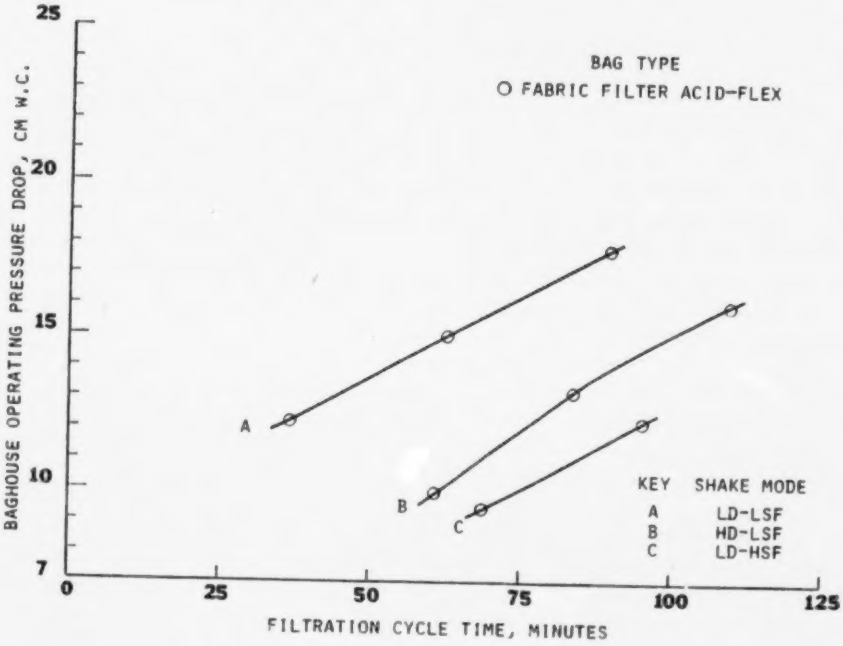

Figure 4. Comparison of acid-flex performance for cleaning modes A, B & C.

The curves displayed in Figure 4 demonstrate the improvement in Acid-Flex bag performance as the degree of cleaning energy is increased. The curves for modes A and C depict the improved operating levels obtained with the high shake frequency, while curves A and B depict improvement related to the higher deflation pressure drop across the bags.

The normal 10 sec. shake duration was extended to 30 sec. within several cleaning modes and for several bag types. Results indicated no appreciable improvements in cleandown; thus, use of an extended shake duration was discontinued.

Selection of the optimum cleaning mode must be based not only on performance characteristics, but also on the degree of physical wear due to fabric flexing with each cleaning cycle. Economics dictate achieving a minimum bag life before attempting to improve operating pressure drop levels and the resultant annual operating costs.

Effect of Coal Type

Two coal types were fired at Harrington Station during this study. The 50:50 blend of Wyoming and New Mexico coals was fired for the first 2 test weeks and corresponded to 2 of 3 weeks testing for the silicone/graphite bags.

A comparison of the performance characteristics for the silicone/graphite (S/G) bags in Figures 4 and 1 would appear to indicate differences related to coal type. In Figure 4, the S/G bags are closely grouped with the two Teflon B bags for cleaning mode A. These data were generated when only Wyoming coal was being fired. The same curves for cleaning mode B in Figure 1 find the S/G bags demonstrating an appreciably higher level of performance. The S/G curve in Figure 1, however, was generated during Wyoming/New Mexico blend firing while the other curves of Figure 1 relate to Wyoming coal only. It would appear from this single case that the Wyoming/New Mexico coal blend resulted in better performance levels for the S/G bags than those observed for Wyoming coal only. This observation illustrates the sensitivity and specificity of the fabric/cake interface, evidenced in this and other studies on fabric/cake characterization.

Collection Performance Measurements

The control device characteristic of practical importance is that of overall collection performance. This performance can be described and measured by the emissions which penetrate the device and pass into the atmosphere. Collection performance and fractional efficiency are a function of inlet particle size distribution, as well as other variables.

Cumulative and differential inlet particle size distribution curves are shown in Figures 5 and 6, respectively, for Amarillo and three other utility PC boilers. As illustrated, the size distribution at Harrington Station falls in the same general range as the other sites.

Since fabric filters with glass bags typically deliver efficiencies in the range of 99.8 percent or higher, only a moderate effort was made to document collection performance for the four bag types. A summary of the inlet and outlet loadings, efficiency, and emission levels in ng/J are presented in Table 7. All four bag types performed at a level which yields emissions an order of magnitude less than the New Source Performance Standard (NSPS) of 13 ng/J (0.03 lb/MBtu). Figure 7 shows fractional penetration for the Acid-Flex and Criswell Teflon B bags.

Electrostatic Effects

It has been speculated that electrostatic effects may be a contributing factor to the bag cleaning problems at Harrington Station. A cursory attempt was made to measure the electrostatic voltage levels present on the silicone/graphite bags in the pilot baghouse. The methodology was the same as that employed by Bob Donovan, Research Triangle Institute, on the Harrington baghouse.[6]

A cage voltage measurement was made by attaching a Type 430 stainless steel screen (0.0075-inch wire, 24 mesh) cage to the bottom of the middle bag in the pilot baghouse. The cage was attached to the bag by sewing it to the bag cuff at the cage top, middle, and bottom points in such a way that no penetration of the filtering surface of the bag was required. The cage was 25.4 cm high and was constructed such that the diameter was only slightly larger than that of the bag. A Teflon-shielded cable from the cage was passed through the adjacent glass window jamb and coupled to an electrometer immediately adjacent to the baghouse compartment.

The profile of cage voltage measurements over two typical cleaning/filtration cycles is shown in Figure 8. A detailed analysis or hypothesis of the resultant effect on bag pressure drop is beyond the scope of this report. However, it appears that sufficient charge levels were shown to exist to be a potential contributing factor to pressure drop problems and to indicate the need for further definition, clarification and evaluations.

RECOMMENDATIONS

Reduction of operating pressure drop at Harrington Station:

- Evaluate higher shake frequencies and monitor bag at quarterly intervals via diagnostic tests (i.e., Muller Burst Strength, Tensile Strength, MIT Flex Fold tester, etc.).

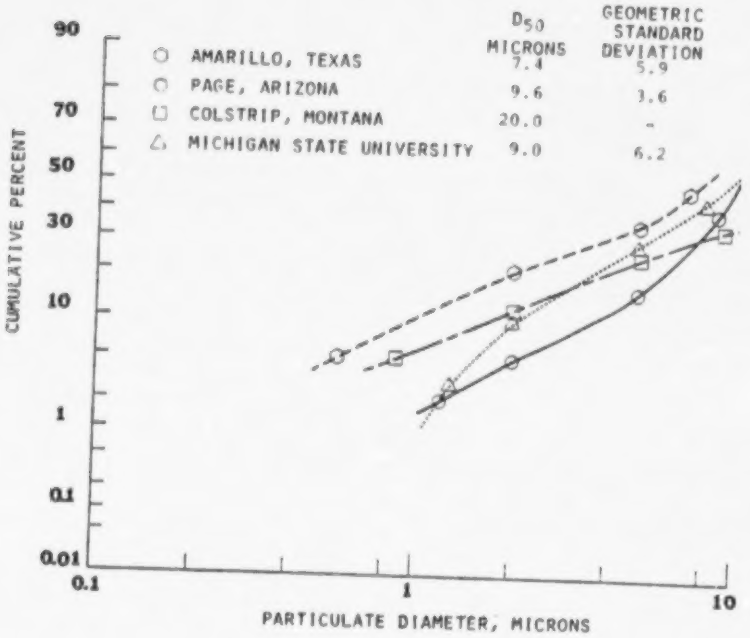

Figure 5. Boiler effluent cumulative particle size distributions at four power plants.

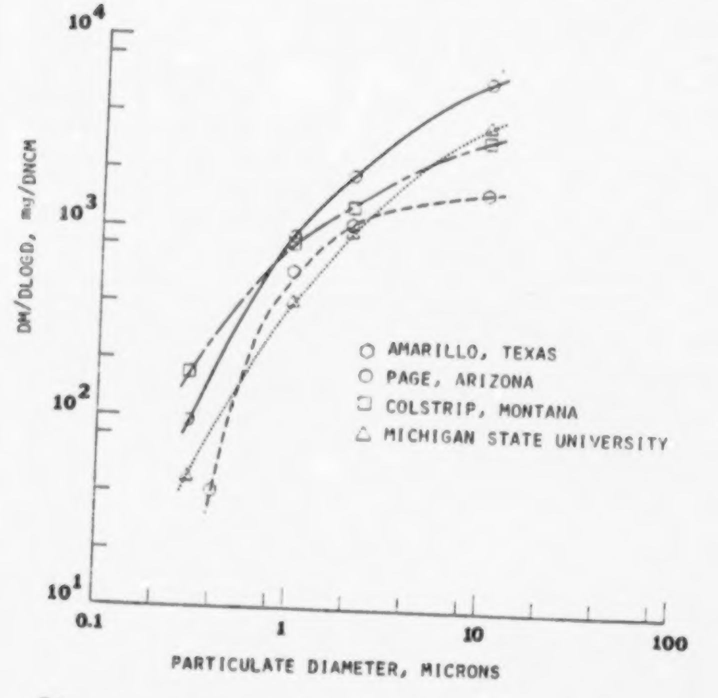

Figure 6. Comparison of boiler effluent fractional size distribution at four power plants.

TABLE 7. SUMMARY OF PARTICULATE CONCENTRATION MEASUREMENTS

Bag Type	Average Inlet Loading	Average Outlet Loading	Efficiency	*Emission Level
	gm/DNCM	gm/DNCM	Percent	ng/J
**Criswell Graphite-Silicone	3.2	0.0038	99.88	0.71
Fabric Filter Acid Flex	2.4	0.0018	99.92	0.34
Menardi Southern Teflon B	2.4	0.0007	99.97	0.13
Criswell Teflon B	2.4	0.0006	99.975	0.11

* Current NSPS 13 ng/J

** 1:1 blend of Wyoming and New Mexico coals. All others Wyoming coal.

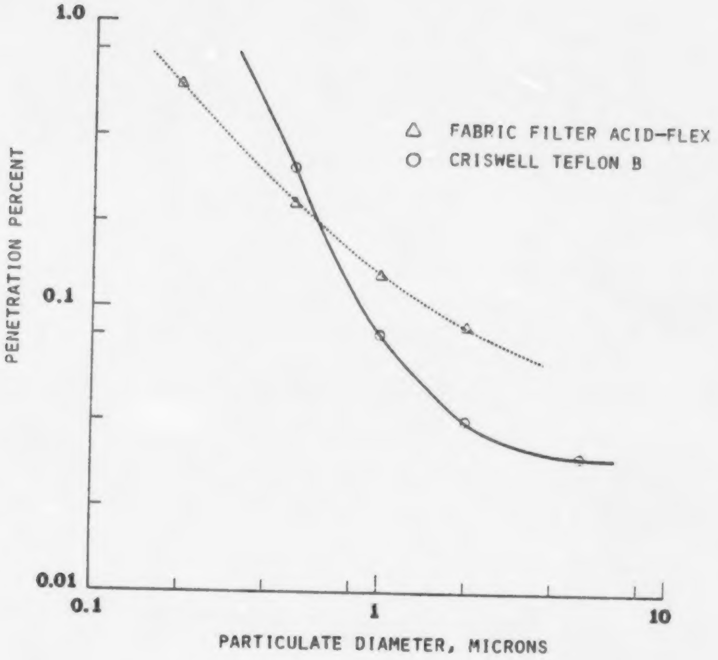

Figure 7. Fractional penetration characteristics for two bag types.

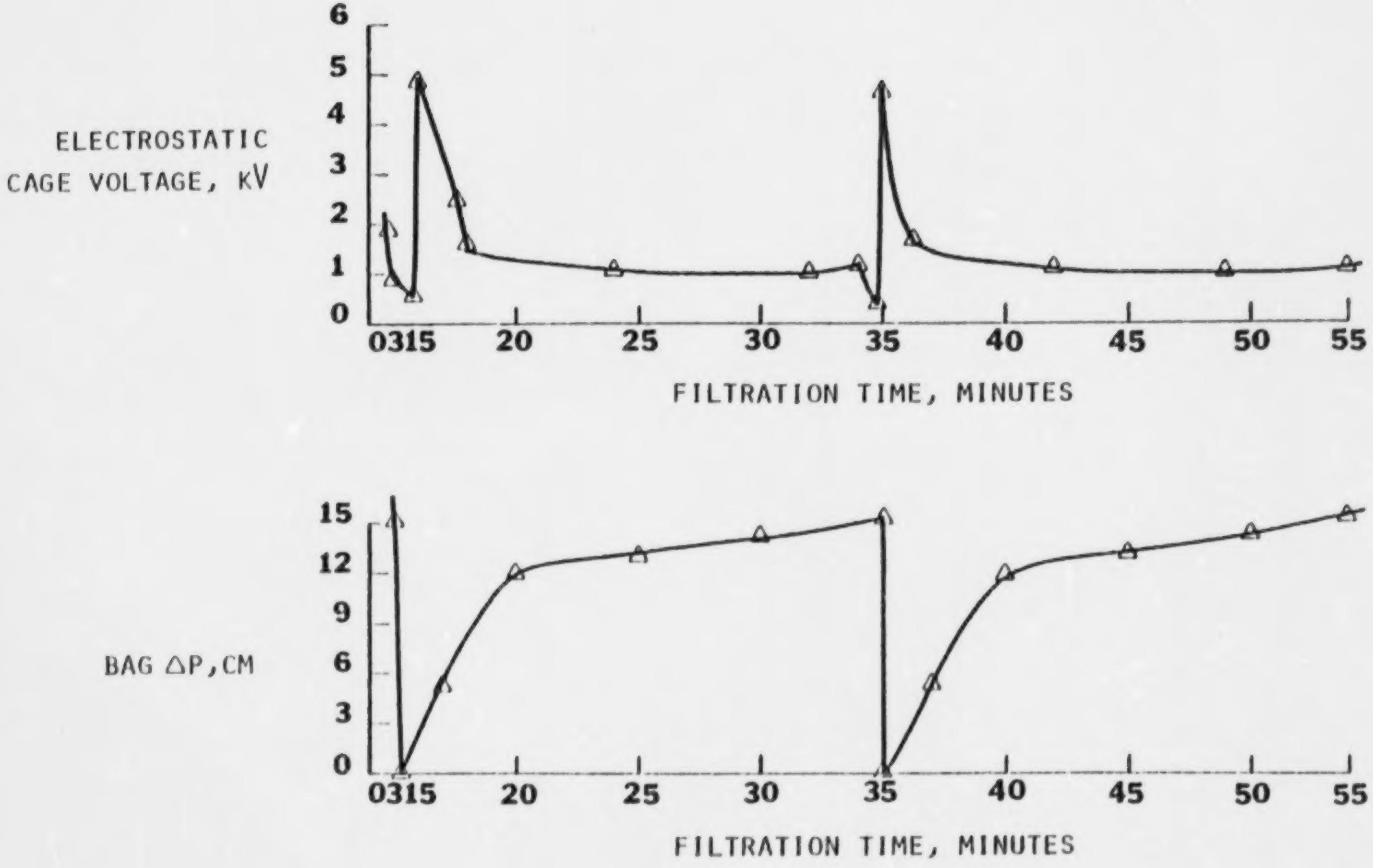

Figure 8. Electrostatic cage voltage profile for two typical cleaning cycles.

- Evaluate performance characteristics of Acid-Flex or an equivalent fabric.

- Evaluate performance characteristics of higher deflation pressures with ring bags.

Suggested future studies:

- Extend characterization of electrostatics at Harrington and other coal-fired boiler/baghouse sites.

- Develop improved hardware and methodology for experimental pilot-scale determination of specific cake resistance coefficients (K_2).

REFERENCES

1. Lipscomb, W.O. Environmental Protection Agency Fabric Filter Program - A Comparison Study of Utility Boilers Firing Eastern and Western Coal. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Volume 2. Fabric Filters and Current Trends in Control Equipment, Venditti, F.P., J.A. Armstrong, and M. Durham (eds.). Research Triangle Park, N.C., U.S. Environmental Protection Agency, February 1979. Publication No. EPA-600/7-79-044b. p. 53-74.

2. Dennis, R., and H. A. Klemm. Fabric Filter Model Format Change: Volume 1. Detailed Technical Report. GCA Corporation, GCA/Technology Division. Bedford, Massachusetts. Publication No. GCA-TR-78-51-G(1). January 1979. 169p.

3. Faulkner, G., and K.L. Ladd. Startup, Operation and Performance Testing of Fabric Filter System - Harrington Station, Unit No. 2. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Volume 2. Fabric Filters and Current Trends in Control Equipment, Venditti, F.P., J.A. Armstrong, and M. Durham (eds.). Research Triangle Park, N.C., U.S. Environmental Protection Agency, February 1979. Publication No. EPA-600/7-79-044b. p. 219-232.

4. Hall, R.R. Mobile Fabric Filter System: Design Report. GCA Corporation, GCA/Technology Division. Bedford, Massachusetts. October 1974. 73p. NTIS No. PB246-287/7BA.

5. Lawless, P.A. Analysis of Cascade Impactor Data for Calculating Particle Penetration. U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory. Research Triangle Park, N.C. Publication No. EPA-600/7-78-189. September 1978. 39p.

6. Donovan, R.P. Passive Electrostatic Effects in Flyash Fabric Filtration. Presented at the Second Symposium on the Transfer and Utilization of Particulate Control Technology. Hosted by the U.S. Environmental Protection Agency, Research Triangle Park, N.C., and the Denver Research Institute, University of Denver. Denver, Colorado, July 25, 1979.

7. Emission Test Results: Harrington No. 1. C-E Power Systems, Combustion Engineering, Inc. Windsor, Connecticut. June 1977. 24p.

8. Chambers, R. Personal Communication. Southwestern Public Service Company, Harrington Station. Amarillo, Texas. March 6, 1979.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Southwestern Public Service Company personnel for their assistance and cordial cooperation, and to Dale Harmon and Jim Turner, EPA, Technical Project Officers.

PASSIVE ELECTROSTATIC EFFECTS IN FABRIC FILTRATION

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ABSTRACT

Electrical charge transport accompanies the flow of dust and flyash through particulate control equipment. In a fabric filter these charges can accumulate on the fabric and other electrically isolated regions. The magnitude of the charge buildup depends upon the electrical properties of both the dust and the fabric and especially the relative humidity of the gas stream. This paper presents laboratory measurements of fabric charge accumulation in both pulse jet and shaker-cleaned baghouses. Brief field measurements show similar charging patterns. No effect on baghouse performance can yet be unambiguously attributed to these charges.

PASSIVE ELECTROSTATIC EFFECTS IN FLYASH FABRIC FILTRATION

That electrical charges exist on flyash and other aerosol particles is well known.[1] Such charges arise: 1) because of charge exchange between neutral materials in contact and their subsequent separation, or 2) because of ion capture by the particles and the resultant Boltzmann charge equilibrium. Particle deposition or collection is necessarily accompanied by charge deposition and collection; and particle flow is to some degree a charge flow, as evident by the pipe charging effects brought about by particle flow through that pipe.[2]

It is these charging effects that make up the passive electrostatic effects to be discussed in this paper. These effects are passive because no overt charging action is required to create the charges; the charges are an inherent property of virtually all flowing dust systems. The questions to be considered include:

1. What is the magnitude of these passive charges in a baghouse and on what does the magnitude of these charges depend?
2. What influence, if any, do these charges have upon baghouse performance?

BACKGROUND

Measurements of voltage buildup on the support cages of a pulse jet fabric filter have previously been reported.[3,4] This measurement, shown schematically in Figure 1, consists simply of connecting an electrometer to the support cage of a bag and recording current or voltage during operation.

For voltage measurements the electrical resistance of the fabric determines the "load" resistance across which the electrostatic voltage is measured. Physically, this load resistance is the electrical resistance of the fabric separating the cage collar from the venturi shoulder. When the resistive coupling to electrical ground dominates the cage voltage, the magnitude of the cage voltage is directly proportional to the fabric resistance. For conductive fabrics an insulating sleeve must be added between the fabric and the venturi in order to support a significant cage voltage.

For current measurements the electrical resistance between the cage and the collar should exceed the input resistance of the electrometer by several orders of magnitude. Again, for electrically conducting fabrics, an insulating sleeve is necessary in order to make a meaningful measurement.

Previous publications summarized the initial observations of such measurements[3] and noted a correlation between high cage voltage and dust penetration through the bag.[4] This correlation has been explored further using different fabrics as described in the first part of this paper. A second measuring configuration, appropriate for inside-out filtration, was subsequently developed and used to make measurements on both a field installation and a laboratory shaker baghouse. These experiments are also described in this paper.

LABORATORY PULSE JET EXPERIMENTS

As an extension to the measurements reported in Reference 4, a fresh set of fabrics was obtained through the courtesy of E. de Garbolewski of W.L. Gore Associates. Table 1 lists these fabrics, their Run Identifiers, and some properties. The set of four different fabric types was prepared so that each differed from another only in its electrical properties or in the addition of a specific compositional change--the Gore Tex* layer. The number contained in the Run Identifier gives the sequence in which the runs were carried out.

When all cages of the nine bag array are tied together electrically, a typical composite cage voltage appears as sketched in Figure 2. Three quantities are defined in Figure 2: 1) V_c is the value of cage voltage immediately prior to the reverse pulse cleaning spike; 2) ΔV_c is the height of the voltage spike induced by the cleaning pulse; and 3) τ is the time required for the cage voltage to recover to 1/e of its value prior to cleaning.

V_c and ΔV_c correlate with dust penetration through the fabric as shown in Figure 3. Each datum point in Figure 3 represents the average of two sequential measurements of dust penetration, both values being determined by a 20 minute sampling of the outlet. The cage voltage for each datum is the arithmetic average of 20 measurements. The standard deviation of the cage voltage is about 5% of the mean when, as is true here, all cages are tied together electrically.

Cage voltage and dust penetration both correlate with relative humidity. Because of this dependence, relative humidity was used as an independent control of cage voltage over a limited range.

With fixed inlet dust loading and constant air-to-cloth ratio, the buildup of bag pressure drop between cleaning pulses was lower at 70% relative humidity than at either 50% or 30% relative humidity. The absolute pressure drop was also lower at the high relative humidities. No dependence of these pressure drops upon cage voltage was apparent.

The relationship between flyash penetration and relative humidity is emphasized by replotting the V_c data of Figure 3 in Figure 4. The shaded regions represent the data envelope of each fabric. All data in Figure 4 were measured after 6 hours of operation at the desired set point on the humidity control unit. Operation at each relative humidity was repeated with sequencing in the opposite directions; for example, 50%-30%-70%-70%-30%-50%. Sequence effects do exist in that the data collected at a given relative humidity depend on the relative humidity of the immediately preceding datum point. For example, the dust penetration measured at 70% relative humidity depended on whether the preceding test point was at 30% or 70% relative humidity. This observation implies that the 6 hour equilibrating time allowed was inadequate and that a major source of error in collecting the data was failure to reach a steady state at each value of relative humidity.

Even so the trend toward reduced flyash penetration at high relative humidity is clear for all these fabrics. That relative humidity also correlates with cage voltage for a given fabric raises the possibility that the relative humidity dependence portrayed in Figure 4 originates from electrostatic forces. Indeed one major reason for including epitropic blends in the fabric test group was to explore this possibility.

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*Registered Trademark of W.L. Gore & Associates, Inc.

The preliminary observation of these evaluations is to refute this electrostatic force hypothesis as an explanation of the dependence of flyash penetration upon relative humidity. In Figure 4 flyash penetration through the epitropic polyester fabric (PJ53) is comparable to that through the standard polyester (PJ50) in spite of the essentially negligible cage voltage measured during epitropic polyester operation. While the Gore Tex/polyester fabric differs from the Gore Tex/epitropic polyester fabric in absolute dust penetration, both fabrics exhibit the same general relative humidity dependence and it is this property rather than the absolute values of flyash penetration that is crucial for the electrostatic hypothesis. If the relative humidity dependence is electrostatic in origin, a conductive fabric should remove the charge and eliminate the relative humidity dependence. The epitropic blend failed to eliminate the relative humidity dependence in either of the two samples, although it effectively eliminated the cage voltage of the straight epitropic fiber blended polyester and greatly reduced it for the Gore Tex/epitropic polyester fabric.

These experiments still leave room for doubt, however, because of the composition of the epitropic blended fabrics. The epitropic fibers with which the epitropic polyester fabrics are blended consist of polyester fibers impregnated with carbon black particles. One technique is to draw a bicomponent fiber whose outer layer has a lower softening point than its core. When the outer layer is subsequently softened, carbon black particles can be incorporated into the surface shell but the fiber retains most of its original dimensions because of its unaffected core component. The resulting fiber is one with a highly electrically conductive surface.

In the preparation of epitropic fabrics a small percentage of these epitropic fibers blended with conventional polyester staple fibers (5% is typical, although 3.5% was the blend percentage in our samples) produces a fabric of greatly reduced surface resistivity which is useful for eliminating static charge buildup in textile products.[5] The presence of these epitropic fibers in the test fabrics was to reduce the electrical resistance between the cage and the venturi shoulder (electrical ground) to 10^4 to 10^6 ohms, preventing the buildup of any significant charges on the cage.

At the fiber level, however, most of the fibers are not coupled to the cage by a conductive fiber--96.5% of the fibers are still the relatively non-conductive polyester. The fabric surface seen by the incoming dust could still be much the same as for the 100% polyester fabric, even though the cage is well coupled to electrical ground.

Plans are underway to extend these measurements to 100% stainless steel felt fabrics. Here all fibers should be closely tied to electrical ground and no charge accumulation should occur initially. As the dust cake builds up, the electrical properties of the dust will impede charge transfer to the conductive fabric but this interference requires some minimum operating time before becoming significant.

BAG DUST LOAD

A second independent hypothesis seeking to explain the relationship between relative humidity and flyash penetration also invokes electrostatic forces. In this model the role of charges building up on the fabric surface is to introduce an electrostatic force which binds the dust to the fabric and hence creates a larger dust load on the bag than would exist in the absence of such electrical forces. Increased dust load on the bag in turn is then postulated to cause increased dust penetration and higher pressure drop.[6,7]

To investigate this hypothesis total bag weights following operation at various relative humidities were measured. The technique was to stop the filtration cycle immediately after the Row 3 cleaning pulse had fired. The baghouse was opened gingerly and a large plastic bag slipped over the dusty bag, including its cage, before demounting. Once the plastic cover was in place so as to catch dust inadvertently shaken loose during removal, the bag was demounted and weighed--plastic bag, dusty fabric, and cage together. Each of the nine bags were weighed one after the other and then remounted at the same location in the baghouse for the next run.

These admittedly crude weighings uniformly confirmed a dependence of bag dust load upon relative humidity, the lowest dust loads on the bag occurring at the highest values of relative humidity.

Table 2 summarizes a recent data set showing this relationship. The run identifier is PJ54. The bags used in this run were the same polyester bags removed after completing Run PJ50. Nine months after the last PJ50 run each used bag was remounted on a cage, weighed, and inserted in the baghouse for the PJ54 series. Table 2 lists the average weight change in the three bags making up a row after operating for 6 hours at the indicated relative humidity. Inlet loading for all these data was 9 g/m^3 (4 $grains/ft^3$). Total gas flow was 7 m^3/min (250 ft^3/min), yielding an air-to-cloth ratio of 3 cm/sec (6 fpm).

Table 2 and the curves constructed from the data (Figure 5) show a dust load dependence in accordance with the qualitative predictions of the electrostatic model--at high relative humidity, less charge exists on the fabric and also less dust. However this confirmation by no means proves an electrostatic interaction. Other nonelectrostatic mechanisms could also produce the same effect. What is shown is that at high relative humidity (> 60%) less dust ends up on the bag and less dust penetrates the bag. The data do not distinguish between the postulated reduced electrostatic binding forces at the bag surface and some other humidity dependent phenomenon, such as enhanced agglomeration and fallout, which reduces the dust that reaches the bag at high relative humidity even though that quantity fed into the baghouse remains constant for all test humidities.

FIELD MEASUREMENTS

The data reported so far have been collected with a laboratory-sized pulse jet baghouse filtering redispersed flyash and operating at room temperature. Because these conditions are sufficiently different from typical boiler operations, some pause seemed warrented before embarking on a detailed study in order to confirm that the charge buildups detected in the laboratory also occurred in operating field installations.

Measurements were therefore carried out at two field sites:

1. A stoker fed boiler at Kerr Finishing Plant, Concord, NC.
2. Harrington No. 2 unit of Southwestern Public Service, Amarillo, TX.

The baghouse installation at Kerr consists of two parallel modules. At the time of the electrostatic measurements one module operated in a reverse air cleaning mode with woven fiberglass bags; the second module used 100% teflon felt bags cleaned by reverse air with a pulse jet assist. Both modules are outside-in filters and employ steel cages electrically isolated from ground by the fabric. Cage voltage measurement technique therefore was identical to that used in the laboratory.

The flyash from the Kerr boiler appears carbon rich and had coated both fabrics with a black deposit which proved relatively conductive. The electrical resistance between the cage and ground was on the order of 10^6 ohms when measured during the weekend before the Monday startup. Cage voltages at operating temperature and flue gas flow were less than 0.1 volts for both fabrics, as the low values of "load" resistance would anticipate. Only one bag from each module was monitored and each of these had been in service for over a year. The conclusion was that only negligible charge accumulation on the bags could be detected; no measurement of charge on the inlet flyash was made.

Harrington Unit No. 2 includes a pulverized coal boiler fired with low sulfur western coal from Black Thunder Mine in Wyoming. The baghouse is a Wheelabrator Frye unit, cleaned by reverse-deflate air and shake. The fabric in service in the compartment monitored for electrostatic effects was silicone-graphite coated fiberglass. This utility boiler baghouse, as most utility baghouses, is an inside-out filter and hence has no cage with which to monitor voltage or current. To gather data comparable to that measured with the cage electrodes of the outside-in baghouses a 1 m (40 in.) section of stainless steel screen was wrapped around the bottom of one of the 29.2 cm (11.5 in.) diameter bags. This bag was adjacent to the compartment door so that an insulated lead could be easily fed through to an outside electrometer. Electrical resistance between this outside screen "cage" and ground was about 5×10^8 ohms at ambient temperature and no flue gas flow.

The flyash entering the baghouse on Harrington is negatively charged. Brief sampling of current and mass yielded an average charge/mass value of 1.7 μC/g, a value perhaps typical of a low efficiency stage of an electrostatic precipitator.

Immediately upon admission of this charged flue gas to the monitored compartment a large negative voltage appeared on the screen cage. This signal settled down to a steady state value of -100 to -300 V during the filtering cycle, although excursions beyond this range in both directions also occurred.

During the cleaning cycle as gas flow stops, a voltage spike appeared in the trace of cage voltage and the sign of the voltage changed--much like the laboratory observations of pulse jet cleaning except that the transition was slower. During the reverse air, pause, and shake periods the cage voltage was small and usually positive. Upon resumption of flue gas flow the large negative signal reappeared and relaxed to its previous steady state range, typically -100 to -300 volts.

This type of behavior generally conforms with the prediction of a simple RC equivalent circuit as sketched in Figure 6. This circuit is identical to that previously postulated for the pulse jet cage voltage. Flue gas flow is assumed to produce a square wave voltage source, V_E, that is coupled through an effective R_2 and C_2 to the detecting screen cage, V_{cage}. The cage itself is coupled to ground by an effective R_1 and C_1. Under such assumptions V_{cage} responds to a square wave input V_E as shown in Figure 7. The key qualitative point being made is that the gas on/gas off voltage spikes and sign changes observed in both the lab and the field can be explained in terms of simple RC couplings and a forcing function V_E associated with the gas flow.

The overriding significance of the observations at Harrington is that charge buildup of magnitude and behavior similar to what has previously been observed in laboratory pulse jet equipment, operating with redispersed flyash and at room temperature, is observed in the field with full-scale equipment, reverse air cleaning, and typical flue gas composition and temperature. No unambiguous effect of electrostatic charges upon baghouse performance has been uncovered [illegible] the need to further investigate the existence of such an effect is reinforced.

LABORATORY SHAKER BAGHOUSE EXPERIMENTS

To extend the fabric charge detection measurements to the laboratory shaker baghouse a modified screen cage was added plus a center-line probe within the bag as sketched in Figure 8. The external cage is similar to that employed at Harrington except that it is supported by insulating phenolic hangers rather than tied to the bag itself.

The center-line probe on the inside of the bag also hangs from a top support. Gas flows from inside to outside in this unit and enters at the top of the bag so that the center-line probe is in the entry way of the dusty gas. It detects charges on the incoming dust and the adjacent dust cake that builds up on the inside of the bag.

The external cage is outside the bag on the clean air side of the fabric. It was sized to allow 1.3 cm (½ in.) clearance between the outside of the bag and the screen. However, the fabric loosens and stretches under pressure so that in operation the bag usually makes direct contact with the cage, much like the support cage of the outside-in flowing pulse jet baghouse.

The external cage construction is analogous to the internal cage of the pulse jet; the center-line probe is a new feature in the measurement scheme. Figure 9 shows various views of these electrodes with and without the bag in place. The shaker mechanism (not shown) moves the bottom of the 1.5 m bag at a frequency of 4 cycles/sec and a peak-to-peak displacement of 2.5 cm.

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Various operating cycles using redispersed flyash originally collected from the baghouse hopper at Harrington and a custom sewn silicone-graphite fiberglass bag are now underway with these electrodes in place. Typical electrode voltage traces are sketched in Figures 10 and 11. Figure 10 shows an early current and voltage plot measured with the center-line probe. While not recorded simultaneously, these curves were recorded within 10 minutes of each other and during the first 10 hours of new bag operation. The baghouse operation cycle for these data was 5 minutes filtration - 30 seconds pause - 30 seconds shake - 30 seconds pause - 5 minutes filtration and so on. This rapid cycling mode allows frequent observation of the current and voltage behavior during the regeneration stage but suppresses dust accumulation below that normally expected in field operations.

For all shaker data collected so far, the dust inlet loading has been 6.9 g/m^3 (3 $grains/ft^3$); total gas flow, 0.91 m^3/min (32 cfm) for an air-to-cloth ratio of 2 cm/sec (4 fpm). These conditions are the standard operating conditions for this EPA shaker baghouse, the same conditions at which the majority of all previous shaker evaluations and experiments have been carried out.

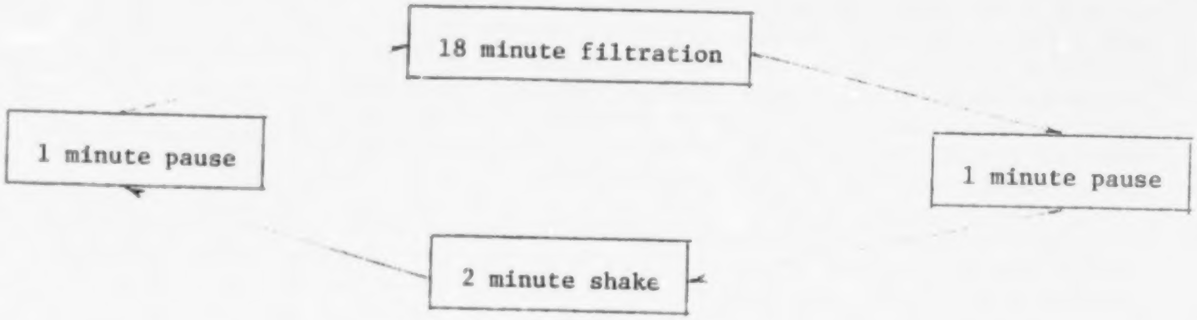
Preliminary observations from these shaker baghouse electrostatic measurements are:

1. the center-line probe detects larger currents and voltages than the cage at low relative humidity (<50% R.H.);
2. the center-line probe current tracks with gas flow--when gas flow stops, the probe current drops to zero;
3. the center-line probe voltage lags the gas flow behaving like a charging and discharging capacitor with respect to a charged gas flow;
4. an inductive coupling may also exist between a charge sheet on the inside of the fabric and the probe, causing probe current during the shake clean and preventing probe discharge by grounding during the pause period (other explanations are possible--the probe current may come from dust reentrained during the shake and the probe voltage may be controlled by charge on the probe that is isolated from the probe by the resistivity of the flyash); and
5. the cage currents and voltages exhibit the sign changes during gas stop and start that would be predicted from the equivalent circuit of Figure 6 and as illustrated in Figure 7.

The cage voltage and current depicted in Figure 11 generally approximates that seen at Harrington except that the signs are reversed! Since the dust and the fabric are identical in the two experiments, the changing charge sign on the dust and on the cage presumably reflects the different charging properties of the dust feed lines and the gas induction system. The Harrington ducts are steel; the laboratory feed lines are rubber.

A second general conclusion of the experiments is that the charge appearing on the bags is dominated by the charge on the incoming dust rather than any triboelectric interaction between the dust and the fabric as previously postulated.[3,4] The crucial triboelectric interactions seem to occur upstream of the baghouse.

The double electrode configuration in the shake baghouse has now been switched to a longer filtration period, more representative of field operation (and previous laboratory work). This cycle consists of the following sequence:



About 100 hours operation have now been logged under these conditions. Probe currents decrease with increasing relative humidity, resulting in reduced probe voltage and cage voltage at high relative humidity. This dependence on relative humidity is similar to that previously noted in the pulse jet experiments.

STATUS SUMMARY

What has been shown is that electrical charges do accumulate in standard baghouse operation. The magnitude of these charges depends on the electrical properties of the dust and the fabric as well as the relative humidity of the gas stream. No unambiguous influence of these charges upon baghouse performance has yet been identified and such an influence is deemed necessary before more detailed modeling of the charging/discharging process. Such a relationship seems highly likely in view of reported observations of electrostatically assisted fabric filtration.[8] The next phase of this EPA work is to measure and control inlet dust charge as this variable appears to be the chief source of passive charges. These experiments will bridge the gap between passive and active electrostatic effects in fabric filtration.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the contributions of: E. de Garbolewski, W.L. Gore Associates, who donated four sets of fabrics for the pulse jet measurements and critiqued the pulse jet experimental plans and results; J. McKenna, J. Mycock, and R. Gibson, Environmental Testing Services, who hosted the Kerr field measurements; K. Ladd and R. Chambers, Southwestern Public Service, who hosted the field measurements at Harrington; and A. Ranade and P. Lawless, Research Triangle Institute, who participated in and contributed to all phases of the work.

REFERENCES

1. Whitby, K.T. and B.Y.H. Liu. "The Electrical Behavior of Aerosols." Chap. 3, pp.59-86 in *Aerosol Science*, edited by C.N. Davies, Academic Press, New York, 1966.

2. Masuda, H., T. Komatsu, N. Mitsui, and K. Iinoya. "Electrification of Gas-Solid Suspensions Flowing in Steel and Insulating-Coated Pipes." *J. of Electrostatics* 2, 1976/1977, pp.341-350.

3. Donovan, R.P., R.L. Ogan, and J.H. Turner. "Electrostatic Effects in Pulse-jet Fabric Filtration of Room Temperature Flyash." *Proceedings of the Engineering Foundation Conference, "Theory, Practice and Process Principles for Physical Separations*," Asilomar, 1977.

4. Donovan, R.P., R.L. Ogan, and J.H. Turner. "The Influence of Electrostatically-Induced Cage Voltage Upon Bag Collection Efficiency during the Pulse-jet Fabric Filtration of Room Temperature Flyash." pp.289-327 in *Proceedings of the Third Symposium on Fabric Filters for Particle Collection*, EPA-600/7-78-087, NTIS No. PB 284-969, June 1978.

5. Ellis, V.S. "Epitropics--Third Generation Conductive Fibres." *Textile Manufacturer and Knitting World* 101, July 1974, pp.19-23.

6. Leith, D., M.W. First, M. Ellenbecker, and D.D. Gibson. "Performance of a Pulse-jet Filter at High Filtration Velocities." pp.11-25, in *Symposium on the Transfer and Utilization of Particulate Control Technology: Vol. 2 Fabric Filters and Current Trends in Control Equipment*, EPA-600/7-79-044b, NTIS No. PB 295-227, Feb. 1979.

7. Dennis, R., R.W. Cass, and R.R. Hall. "Dust Dislodgement from Woven Fabrics Versus Filter Performance." *J. Air Pollut. Control Assn.* 28, Jan. 1978, pp. 47-52.

8. Lamb, G.E.R., and P.A. Costanza. "Role of Filter Structure and Electrostatics in Dust Cake Formation." Presentation at the Second Symposium on the Transfer and Utilization of Particulate Control Technology, Denver, CO., July 1979.

Table 1. Pulse Jet Fabrics

Run No.	Fabric Description	Sample Bag Weight (g) (1 bag, nominally 1.2 m long, 11.4 cm dia) [4 ft; 4½ inches]	Nominal Collar Resistance at 50% R.H. (ohms)
PJ50	Polyester Felt	220	5×10^9
PJ49	Polyester Felt + Gore Tex Layer	190	
PJ53	Polyester Felt with Epitropic Fibers	236	4×10^4
PJ51	Polyester Felt with Epitropic Fibers + Gore Tex Layer	212	5×10^6
PJ52	Teflon Felt	415	2×10^{12}

Table 2. Bag Weighing Summary, PJ54

Run No.	R.H. (%)	Bag Weight Change* (grams)			Pressure Drops, N/m^2 (in. of H_2O)			C_o, g/m^3 (grains/10^{3}ft^3)	E (%)
		Row 1	Row 2	Row 3	ΔP_F -	ΔP_E =	ΔP_D		
A	51	79.7	48.7	6.0	398 (1.60)	348 (1.40)	50 (0.20)	0.46 (201)	95.5
B	38	84.3	53.0	8.0	460 (1.85)	400 (1.61)	60 (0.24)	0.48 (210)	95.3
C	64	67.9	38.7	-2.7	323 (1.30)	311 (1.25)	12 (0.05)	0.22 (94.7)	97.7
D	66	52.0	26.7	-5.3	323 (1.30)	311 (1.25)	12 (0.05)	0.14 (60.4)	98.6
E	34	89.7	52.3	6.7	386 (1.55)	336 (1.35)	50 (0.20)	0.55 (239.4)	94.6
F	48	83.3	46.7	1.3	398 (1.60)	361 (1.45)	37 (0.15)	0.44 (190.4)	95.7

*Actual bag weight after each run less the following initial weights

Used Bag + Cage + 60 gram plastic bag:

	Row 1	Row 2	Row 3
Left	1490	1490	1500
Center	1473	1495	1483
Right	1500	1485	1481

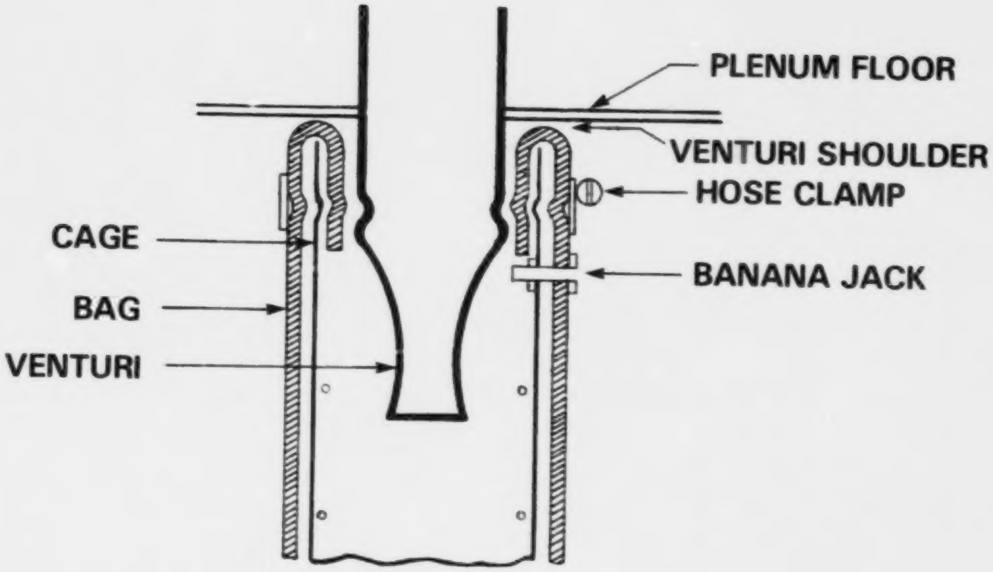


Figure 1. Cage electrical contact, pulse jet baghouse.

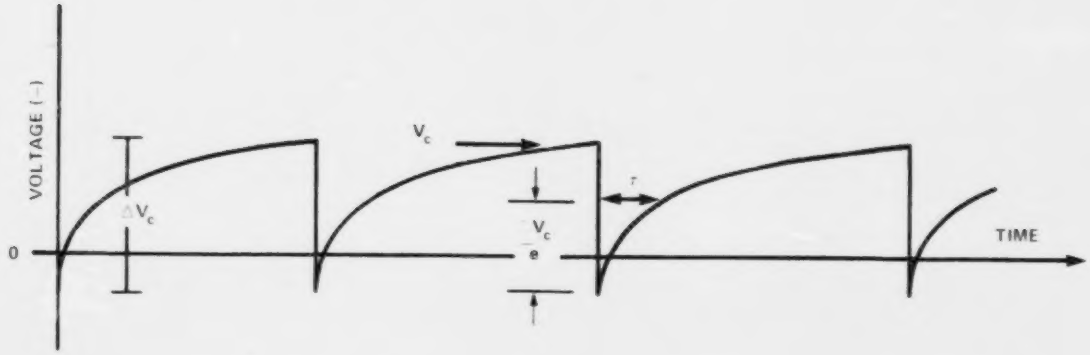


Figure 2. Cage voltage during pulse-jet fabric filtration

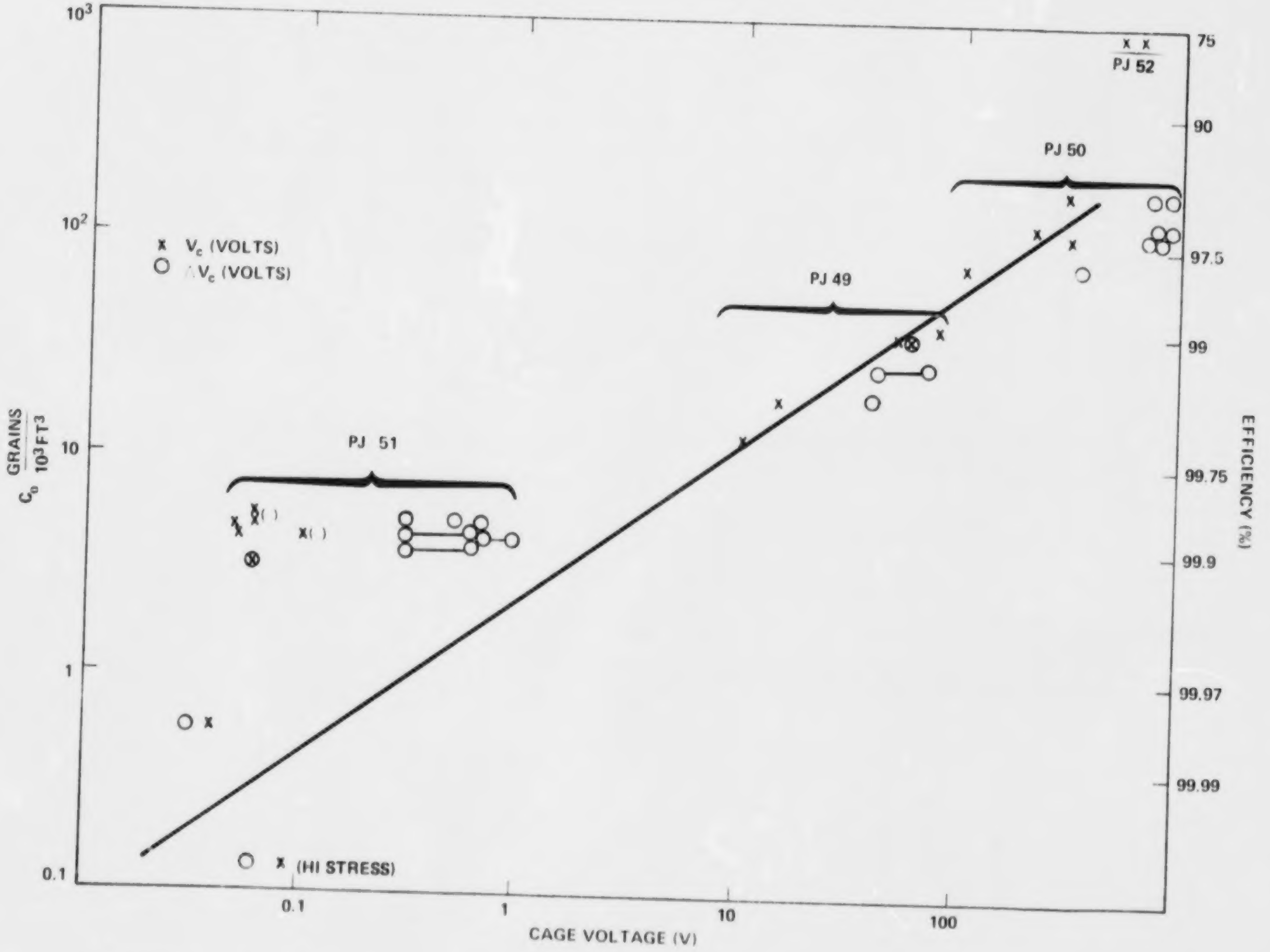


Figure 3. Correlation of cage voltages with outlet concentration.

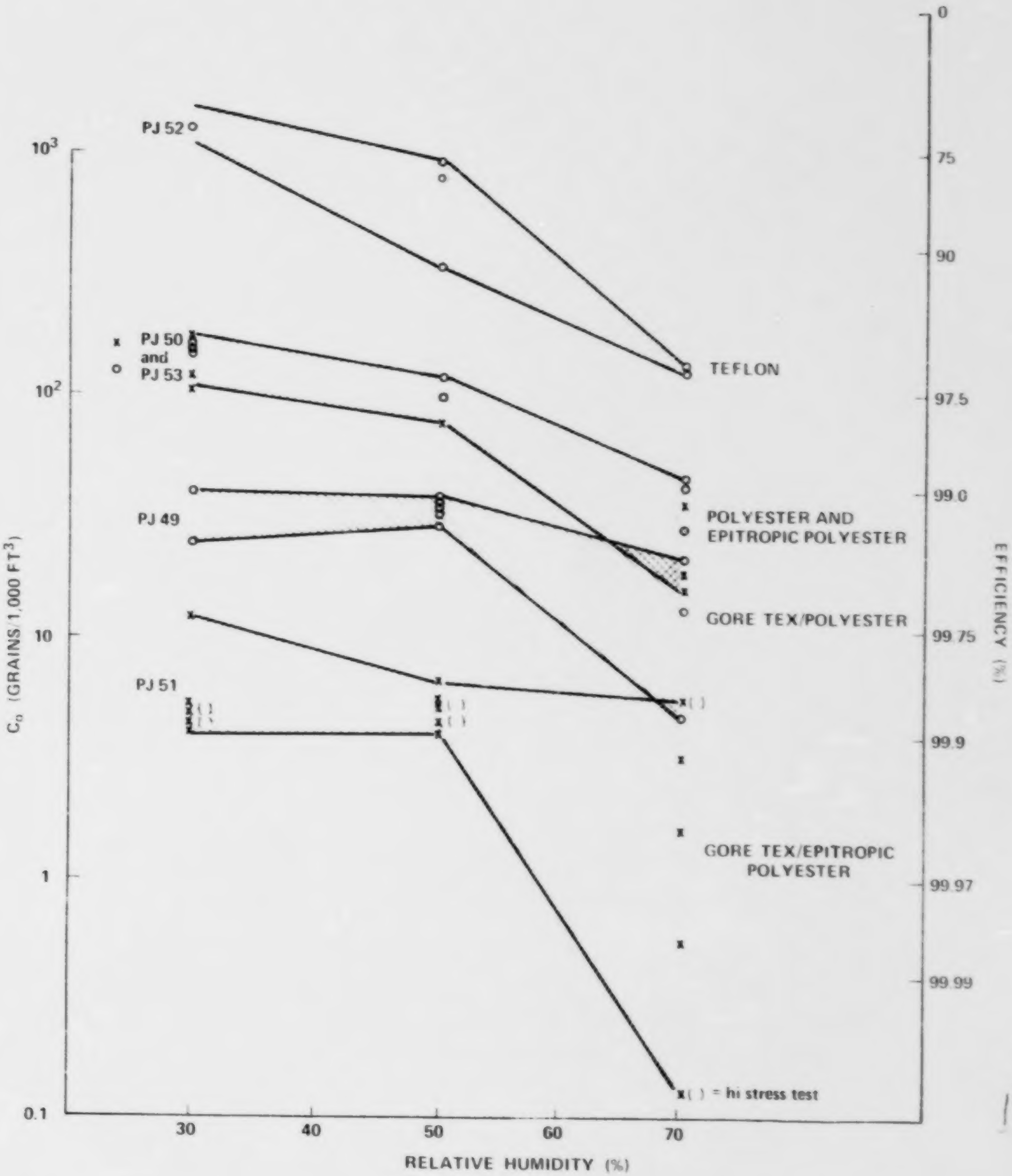


Figure 4. Dependence of dust outlet concentration upon relative humidity.

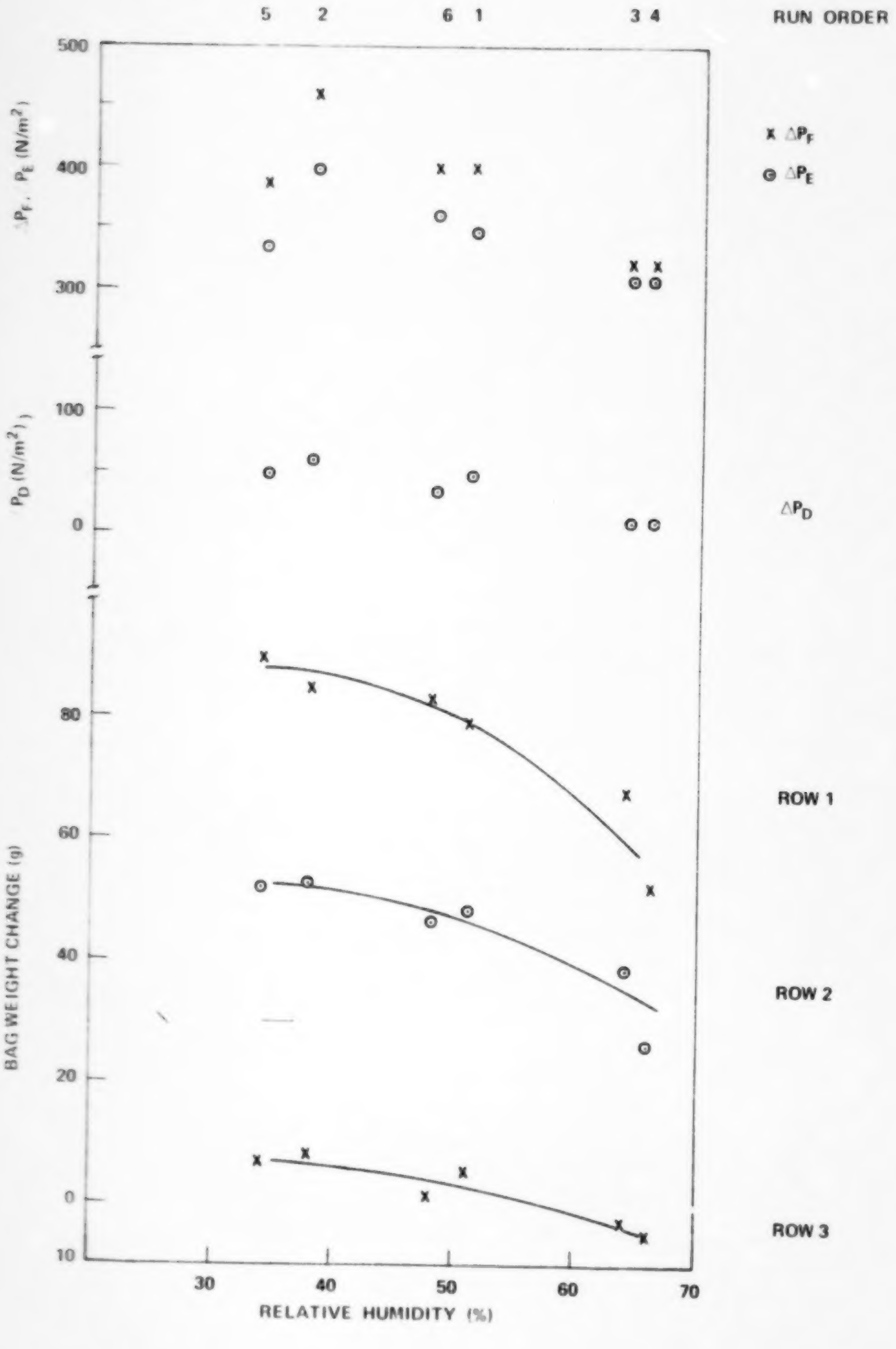


Figure 5. Relative humidity dependence of bag weight changes and pressure drops.

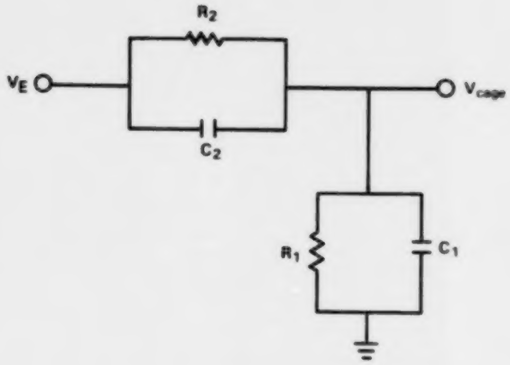


Figure 6. Simple equivalent circuit.

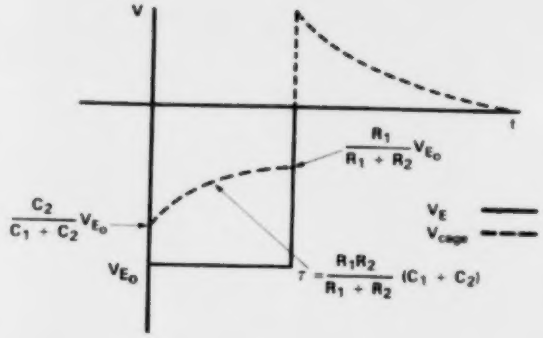


Figure 7. Circuit response.

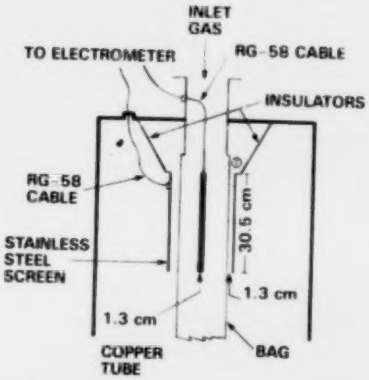
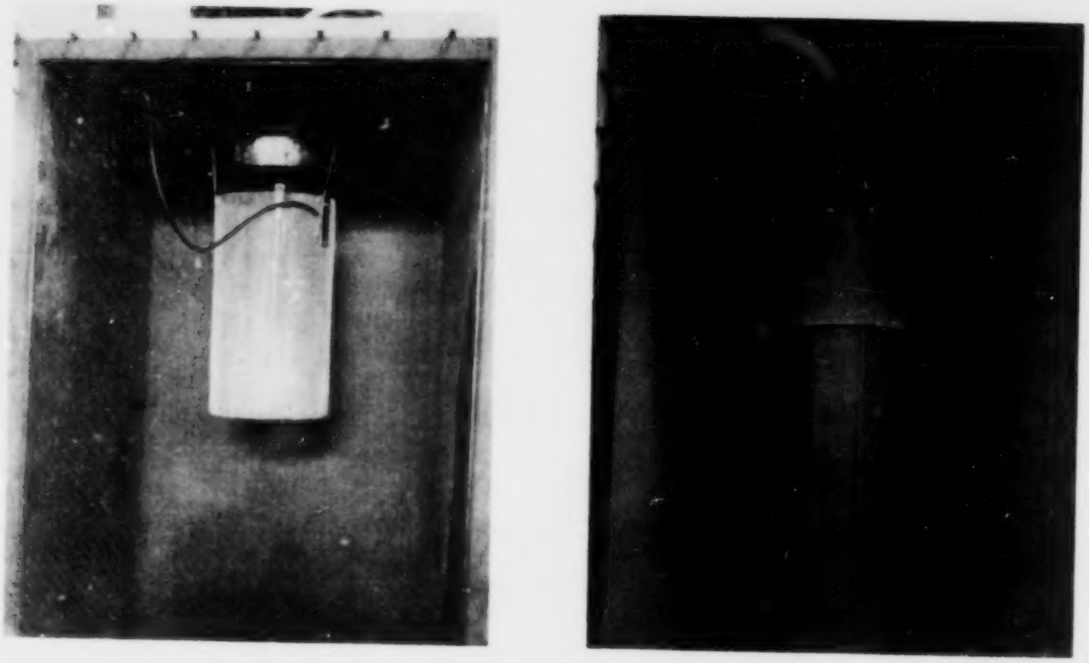
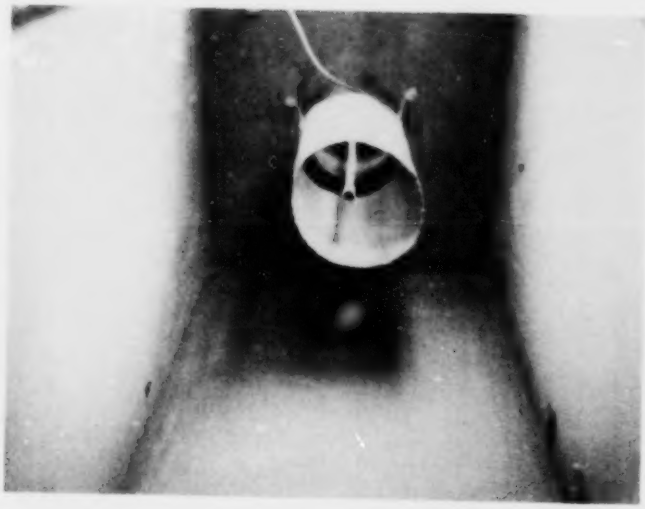


Figure 8. Shaker baghouse electrode configuration.



a. front view.

b. front view, bag in place.



c. bottom view.

Figure 9. Electrodes for shaker baghouse.

[redacted]

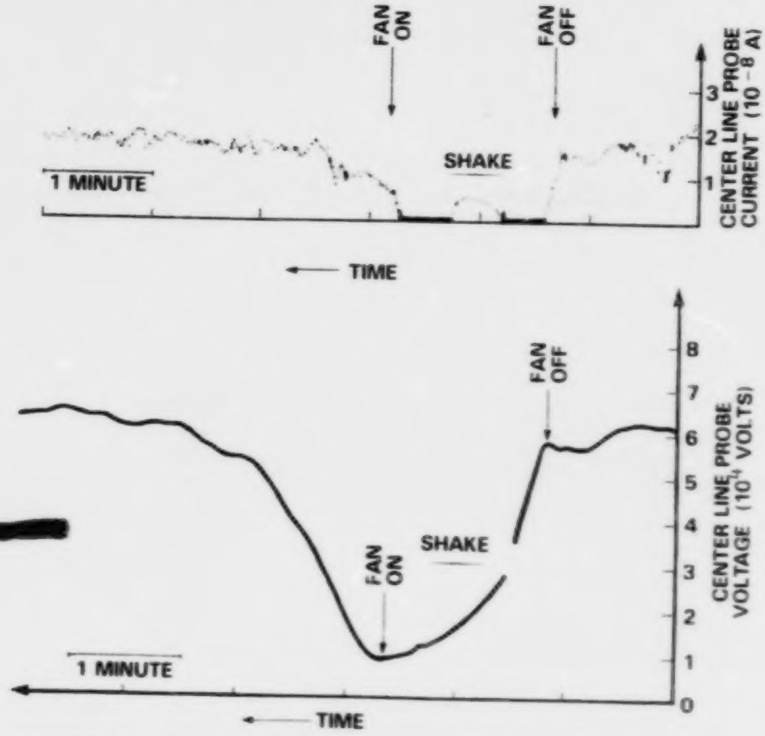


Figure 10. Centerline probe current and voltage.

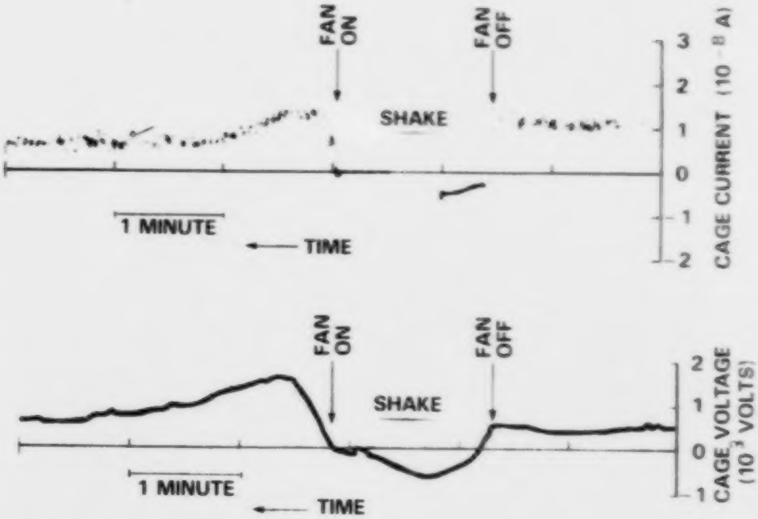


Figure 11. Shaker cage current and voltage.

A WORKING MODEL FOR COAL FLY ASH FILTRATION

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ABSTRACT

A compact mathematical model is described for use by enforcement, design or user personnel to determine whether a fabric filter system can comply with particulate emission regulations. All calculations have been incorporated in the computer program to facilitate model application by control agency and other concerned groups. Given the correct combustion, design and operating parameters, the model will predict emission and pressure loss characteristics. The model user has the option of requesting a summary printout of key performance data or highly detailed results for research purposes. Several built in error checks prevent the generation of useless data. The model considers dust properties and concentration, face velocity, compartmentized operation and cleaning procedures. The model function depends upon the unique fabric cleaning and dust penetration properties observed for coal fly ash and woven glass bags. Examples of model applications are presented including typical data inputs and outputs.

A WORKING MODEL FOR COAL FLY ASH FILTRATION

INTRODUCTION

Fabric filter systems represent an effective and often the only practical means for controlling fly ash emissions from coal-fired industrial or utility boilers. In the latter case, the physical size and cost of large baghouses (often filtering more than 30,000 m^3/min at temperature) demands that the design and operation of the system be undertaken with a priori assurances that compliance with emission regulations can be attained at an acceptable energy expenditure.

To avoid risky extrapolation of design parameters for existing but not necessarily replicate systems to new designs and to reduce dependence on "engineering judgement" as a basis for designing a new filter system, the U.S. Environmental Protection Agency has sponsored the development of a mathematical model for predicting the performance of filter systems (Contract No. 68-02-1438, Tasks 5, 6, and 7). Detailed results of these studies from the inception of the fundamental modeling concepts to the recent publication of a working model for use by agencies responsible for enforcement of emission regulations have been described in the literature.(1-6)

The purpose of this paper is to describe how enforcement personnel can use the filtration model as a diagnostic tool to determine whether a proposed or existing filter system design affords a reasonable chance of successful field performance. The qualification "reasonable" is emphasized because the model output depends not only upon the proper physical description of the filtration process (which we believe to be essentially correct) but also upon accurate definition of key variables necessary to the modeling process.

Model Role

The present model is designed for use with woven fabrics that are cleaned by (a) collapse and reverse flow, (b) mechanical shaking, or (c) some combination of the above. Although not restricted to fly ash filtration, the model is not intended for use with pulse jet cleaned, felt fabrics. A new model based upon GCA studies(7,8) and recent Harvard research(9,10) has been proposed by Dennis and Klemm for predicting performance of pulse jet filters with fly ash and other dusts.(11) Although the present paper deals mainly with the diagnostic applications of the model, it should also be noted that the model may be applied equally well by system designers and equipment users as a predictive device and/or in support of whatever historical or experience backlog is available.

The model discussed in this paper describes the overall performance of real field systems in terms of the variables considered to exert a significant impact on filter performance. Past use of the term "mathematical model" has often referred to specific mathematical relationships between dust, fabric and gas properties and filter performance. Although such correlations have in many cases correctly defined certain aspects of the filtration process, they cannot, taken singly, be used to predict overall filter system performance.

Modeling Approach and Requirements

The new model takes into account that air flow, pressure loss and dust penetration through the many compartments and bags of a sequentially cleaned system will vary from point to point in accordance with the local fabric dust loadings. Because these flow interrelationships are highly complex it is only by means of iteration techniques and a computer that the model can be adapted to the solution of practical problems. Therefore, it was very important to exercise extreme care in designing the model so that it can be used by experienced environmental engineers who are not necessarily specialists in filtration and/or computer technology.

The pollution control engineer wants a relatively uncomplicated prodedure whereby he can input specific values for the controlling filtration and process variables into a predictive model and receive as output a summary of the probable system performance. He is concerned not only with average and maximum particulate emissions but also with the probable ranges in fabric pressure loss and predicted cleaning frequency, the latter information for comparison with design specifications.

PRE-MODELING PROCEDURES

It is emphasized again that the reliability of the filtration model output is only as good as the quality of the data inputs available for the modeling process. Additionally, the degree to which the model user understands the operation of the boiler of interest and the rationale for the design parameters for the existing or proposed fabric filter system will play an important role in model utilization. Again, it must be stressed that the model is normally intended to augment the available data base and not to replace it unless the information quality is suspect.

Before undertaking any modeling operations, a thorough inspection of the filtration plant should be made, preferably by both enforcement and user personnel. This procedure will help to identify specific problem areas that may or have contributed to unsatisfactory performance, e.g., missing or defective bags, lack of thermal insulation, defective gauges, overflowing hoppers, leaking gasketing and signs of corrosion. The above defects should be corrected before comparisons are made with the results of detailed modeling efforts.

BASIS FOR MODEL DESIGN

Working Equations

The developmental aspects for the filtration model have been discussed at length in recent publications.[1-5] It suffices here to point out that the model embraces several well recognized filtration principles that have been reviewed extensively by Billings and Wilder.[8] A listing of the basic equations used to estimate individual filtration parameters and/or to establish their roles within the filtration model is given in Table 1.

Many of these relationships appear in the open literature[5,8] such as the equations used to calculate filter drag, S, or resistance, P, (Equations 1a, 1b, and 4); specific resistance coefficient, K_2 (Equation 7) and specific surface parameter, So, (Equation 9). Certain of the equations were developed, however, in conjunction with recent modeling studies.(1,4,) These include the expression describing nonlinear drag curves (Equation 2), the effect of filtration velocity and dust surface properties on K_2 (Equations 5 and 6), the relationship between the degree of cleaning, a_c, the method and intensity of cleaning (Equation 11-12, 14-16); and finally, the general expressions used to estimate overall filter system drag and penetration (Equations 4 and 20).

New Filtration Concepts

The introduction of three new concepts, however, has made it possible to estimate the performance of a multicompartment filter system in much more realistic fashion than previously possible. The first describes dust separation from woven fabrics as a spalling-off process wherein the application of cleaning energy causes dust separation to occur at the dust layer-fabric interface.[1,2] The above phenomenon permits the use of Equation 4, Table 1, for computation of resultant filter system drag. The second concept is based upon a straightforward description of the fabric cleaning process[1,3,4] that relates the amount of dust removed to the method of cleaning and the prior dust loading on the fabric. Equations 10 through 14, Table 1, depict the types of calculations carried out within the program to estimate the fraction of cleaned fabric area, a_c, by reverse flow cleaning. If mechanical shaking is used, Equations 10, 15, and 16 are employed to compute penetration behavior exhibited by many fabrics woven from multifilament and bulked yarns. Temporarily or permanently unblocked pores or pinholes contribute to extensive penetration of the upstream aerosol such that up- and downstream particle size properties are very similar. Because of this phenomenon, the model treats filter emissions on a mass basis only (Equations 17 through 20).

MODEL FIELD APPLICATIONS

In this section, the actual application of the model is described as intended for use by field engineers to determine whether a proposed or existing fabric filter system is able to reduce fly ash emissions to required levels. The following material represents an abridgement of model operating instructions appearing in a recent EPA report.[4]

Input Variables

For immediate reference, a listing of the input variables used with the filtration model is presented in Table 2. Data inputs are grouped in four

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TABLE 1. SUMMARY OF MATHEMATICAL RELATIONSHIPS USED TO MODEL FABRIC FILTER PERFORMANCE

Equation number	Equation	Comments	Terms and units
(1a)	$S = P/V = S_E + K_2W$	Equations (1a) and (1b), which are used for the linear model, relate filter drag, S, or pressure loss, P, to fabric loading, W. P_L is the limiting pressure loss and W_P the corresponding fabric loading. Cleaning initiated at P_L. S_E is the effective residual drag, W_R the residual fabric loading for the cleaned areas, K_2 the dust specific resistance coefficient and V the face velocity.	$P, P_L = N/m^2$ $S, S_E = \frac{N\text{-}min}{m^3}$ $V = m/min$ $W, W_R = g/m^2$ $K_2 = \frac{N\text{-}min}{g\text{-}m}$ See Figure 1.
(1b)	$P_L = S_EV + K_2V(W_P - W_R)$		
(2)	$S = S_R + K_2W' + (K_R - K_2)W^*(1-\exp(-W'/W^*))$ $W' = W - W_R$	Equations (2) and (3), which are used for nonlinear model, describe initial curvature often seen in S versus W curves and also the later approach to linearity. K_R is the initial slope for curvilinear region, S_R the actual residual drag for cleaned area, and W^* a system constant. If W^* is zero, program automatically uses linear model.	$K_R = \frac{N\text{-}m}{g\text{-}m}$ $S_R = \frac{N\text{-}min}{m^3}$ $W^* = g/m^2$ See Figure 2.
(3)	$W^* = (S_E - S_R + K_2W_R)/(K_R - K_2)$		
(4)	$S = P/V = \left(\sum_{i=1}^{n} \frac{a_c}{S_c} + \frac{a_{u_1}}{S_{u_1}} + \ldots \frac{a_{u_i}}{S_{u_i}}\right)^{-1} A$	Equation (4) describes resultant drag for parallel flow through cleaned and uncleaned regions of fabric surface. The term a_c denotes cleaned fraction of fabric surface with its initial cleaned drag, S_c. "A" refers to total surface fraction and "n" to the total number of fabric elements. Subscript "u" refers to all areas not "just cleaned."	a_c = dimensionless $S_c, S_u = \frac{N\text{-}min}{m^3}$ A = dimensionless = 1.0 See Figures 1 and 2.
(5)	$K_2 = 1.8\ V^{\frac{1}{2}}$	Equation (5) describes effect of face velocity on K_2 with coal fly ash, (MMD = 9 μm and σ_g = 3) and at temperature T = 25°C	MMD = cm^{-1} σ_g = dimensionless T = °C
(6)	$(K_2)_f = (K_2)_m \left[(S_o)_f / (S_o)_m\right]^2$	Equation (6) defines K_2 for filtration conditions (f) when the K_2 value is available for the same dust but with different measured (m) specific surface properties, S_o.	$S_{o_f}, S_{o_m} = cm^{-1}$
(7)	$K_2 = \frac{\mu S_o^2}{\rho_p C_c}\left[\frac{3 + 2(\beta)^{5/3}}{3-4.5(\beta)^{1/3} + 4.5(\beta)^{5/3} - 3(\beta)^2}\right]$	Equation (7) predicts K_2 in terms of gas viscosity, μ, specific surface parameter, S_o, cake bulk density, $\bar{\rho}$, and discrete particle density, ρ_p. Equation (7) used only when no direct K_2 measurements are available. The Cunningham correction, C_c, approaches one for large (fly ash) particles.	μ = poise $\bar{\rho}_p, \rho_p = g/cm^3$ ε = dimensionless C_c = dimensionless
(8)	$1 - \bar{\rho}_p/\rho_p = \varepsilon;\ \bar{\rho}/\rho_p = \beta$		

TABLE 1. (continued).

Equation number	Equation	Comments	Terms and units
(9)	$S_o = 6\left(\frac{10^{1.151 \log^2 \sigma_g}}{\mathrm{MMD}}\right)$	Equation (9) computes distribution specific surface parameter, S_o, from cascade impactor data for a logarithmic normal mass distribution.	$S_o = \mathrm{cm}^{-1}$
		Reverse Flow with Bag Collapse	
(10)	$W_P' = \frac{P_L - S_E V}{K_2 V} + W_R + \frac{C_i V \Sigma t}{2}$	Intermittent, pressure controlled cleaning. Substitution of W_P' from Equation (10) in Equation (11) gives area fraction cleaned, a_c, as function of limiting pressure loss, P_L, and previously cited system parameters. W_P' accounts for the fact that the average W_P' value over the cleaning cycle will exceed the initial values.	a_c = dimensionless
(11)	$a_c = 1.51 \times 10^{-8} W_P'^{2.52}$		
(12)	$a_c = (6.00 \times 10^{-3})\ (V\ C_i\ t_c)^{0.715}$ $t_c = \Sigma t + t_f$	Intermittent, time controlled cleaning. Equation (12) applies when total cycle time, t_c, is given. Note that t_c is the sum of time required to clean all compartments, Σt, plus the time between compartment cleaning, t_f. Face velocity, V, and inlet concentration, C_i, must be nearly constant for safe use of time control.	t_c, Σt, t_f = min $C_i = \mathrm{g/m^3}$ V = m/min
(13)	$W_P = 166.4\ (C_i\ V\ \Sigma t)^{0.284}$	Continuously cleaned system. Equation (13), which shows dust loading on compartment ready for cleaning, applies when $W_P \geq 10$ times W_R. Equation (14) computes a_c for a continuously cleaned system where Σt is the time to clean all compartments.	n = number of compartments
(14)	$a_c = (6.00 \times 10^{-3})\ (V\ C_i\ \Sigma t)^{0.715}$		
		Mechanical Shaking	
(15)	$a_c = 2.23 \times 10^{-12}\ (f^2\ A_s\ W_P')^{2.52}$	Intermittent, pressure controlled cleaning system. Substitution of W_P' from Equation (10) in Equation (15) in conjunction with shaking parameters f and A_s determines a_c. W_P' accounts for the fact that the average W_p value over the cleaning cycle will exceed the initial values.	a_c = dimensionless f = shaking frequency = Hz A_s = shaking frequency = cm
(16)	$a_c = 4.9 \times 10^{-3}\ (f^2\ A_s\ C_i\ V\Sigma t)^{0.715}$	Continuously cleaned system. Equation (16) computes a_c in terms of cleaning parameters f and A_s and the dust accumulation over the time required to clean all compartments ($C_i\ V\Sigma t$).	Σt = time to clean all compartments = min
(17)	$C_o = \left[Pn_s + (0.1 - Pn_s)\ e^{-aW}\right] C_i + C_R$	Equations (17) through (19) are empirical relationships used to compute outlet concentrations, C_o, in terms of incremental increase in fabric loading ($W' = W - W_R$); inlet dust concentration C_i; and local face velocity, V. The term C_R is a constant, low level outlet concentration that is characteristic of the dust fabric combination. Pn_s and a are curve fitting constants for specific systems.	C_i, C_o, $C_R = \mathrm{g/m^3}$ $W = \mathrm{g/m^2}$ V = m/min Pn_s, Pn_t = dimensionless $a = \mathrm{m^2/g}$
(18)	$Pn_s = 1.5 \times 10^{-7} \exp\left[12.7\ (1 - e^{\ 1.03V})\right]$		
(19)	$a = 3.6 \times 10^{-3}\ V^{-4} + 0.094$		
(20)	$Pn_t = \frac{I}{V_t\ IJ} \sum_{i=1}^{I} \sum_{j=1}^{J} Pn_{ij_t}\ V_{ij_t}$	Equation (20) depicts basic iterative structure for defining system penetration at any time, Pn_t as a function of parallel flow through "I" compartments (each subdivided into "J" individual areas) where local face velocities and fabric loadings are variable with respect to time and location.	I = No. compartments J = No. areas per compartment t = time

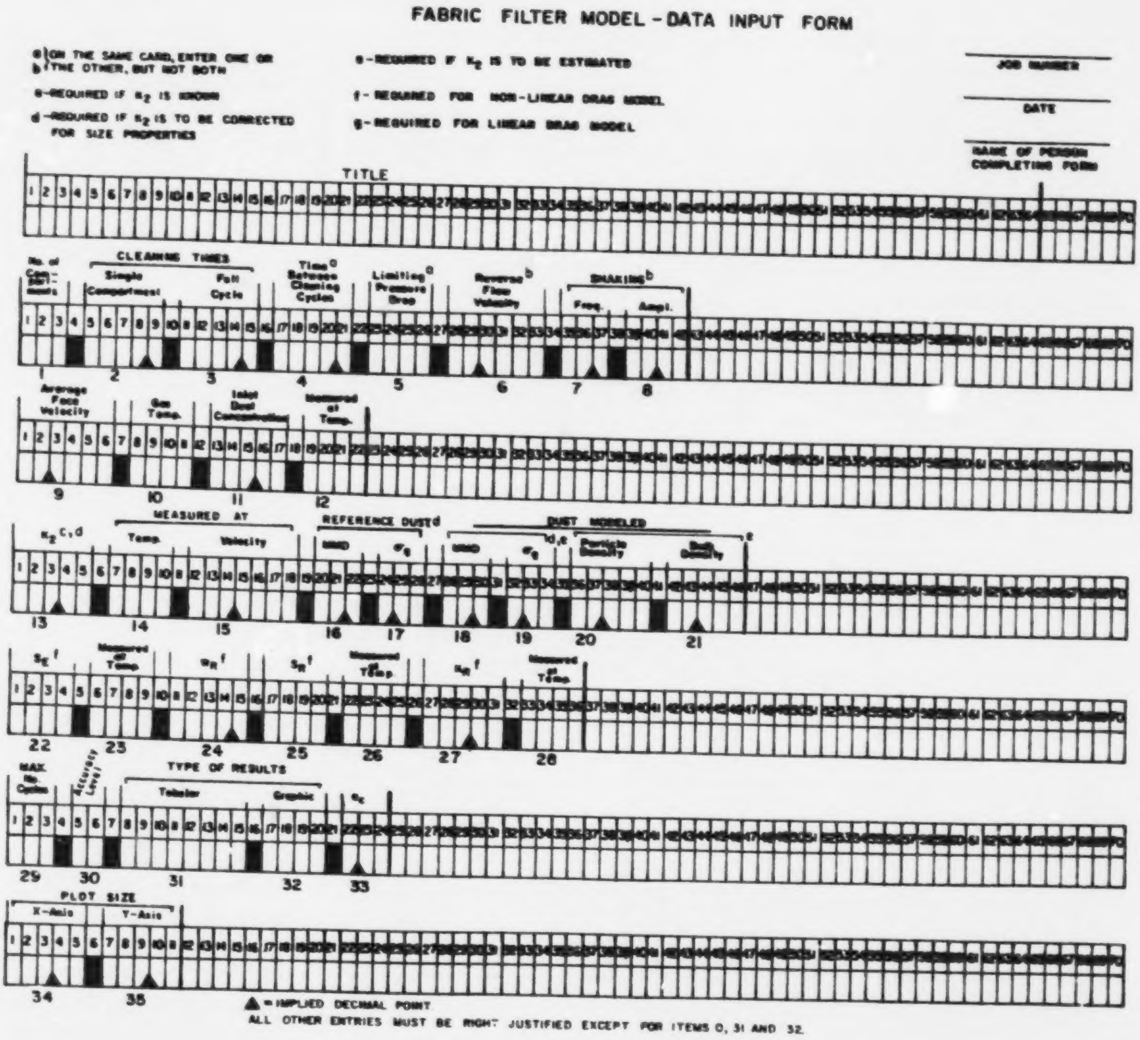
TABLE 2. SUMMARY LISTING OF INPUT DATA FOR FILTRATION MODEL

		Item	Symbol	Units	Card	Valid range	Default*	Note
	0	Title		-	1			
DESIGN DATA	1	Number of compartments	n	-	2	1 to 30		
	2	Compartment cleaning time	Δt	min	2		0.5(Item 3/Item 1)	
	3	Cleaning cycle time	Σt	min	2			
	4	Time between cleaning cycles	t_f	min	2			a
	5	Limiting pressure drop	P_L	N/m^2	2			a
	6	Reverse flow velocity	V_R	m/min	2		0	b
	7	Shaking frequency	f	cps	2			b
	8	Shaking amplitude	A	cm	2			b
OPERATING DATA	9	Average face velocity	V	m/min	3	0.3 to 3.0		
	10	Gas temperature	T	°C	3	>0		
	11	Inlet dust concentration	C_i	g/m^3	3			
	12	measured at temperature of	T	°C	3		25	
DUST AND FABRIC PROPERTIES	13	Specific resistance coefficient	K_2	N-min/g-m	4	0.25 to 10		c,d
	14	measured at temperature of	T	°C	4	>0	25	
	15	measured at velocity of	V	m/min	4		0.61	
	16	measured at mass median diameter of	MMD_1	μm	4	2 to 50		d
	17	measured at geometric standard deviation of	σg_1	-	4 4	2 to 4		d
	18	Mass median diameter of inlet dust	MMD_2	μm	4	2 to 50		d,e
	19	Geometric standard deviation of inlet dust	σg_2	-	4	2 to 4		d,e
	20	Discrete particle density of inlet dust	ρ_p	g/cm^3	4			e
	21	Bulk density of inlet dust	$\bar{\rho}$	g/cm^3	4			e
	22	Effective residual drag	S_E	$N\text{-}min/m^3$	5		350	f,g
	23	measured at temperature of	T	°C	5	>0	25	
	24	Residual fabric loading	W_R	g/m^2	5		50†	f,g
	25	Residual drag	S_R	$N\text{-}min/m^3$	5			f
	26	measured at temperature of	T	°C	5	>0	25	
	27	Initial slope	K_R	N-min/g-m	5			f
	28	measured at temperature of	T	°C	5	>0	25	
SPECIAL PROGRAM INSTRUCTIONS	29	Maximum number of cycles modeled	nc	-	6			h
	30	Accuracy code	0 or 1	-	6	0 or 1	0	
	31	Type of tabular results	-	-	6		Average	i
	32	Type of plotted results	-	-	6			i
	33	Fractional area cleaned	a_c	-	6	>0 to 1		j
	34	x axis length		inches	7		6	k
	35	y axis length		inches	7		5	

*These values are used when no entry has been made for the parameter.

†Used only when K_2 is to be estimated from size properties.

Notes:
- a. Enter item 4 or 5, but not both.
- b. Enter item 6 or 7 and 8, but not both.
- c. Enter items 13 through 15 when K_2 measurement is available.
- d. Enter items 13 through 19 when K_2 measurement must be corrected for size properties.
- e. Enter items 18 through 21 when K_2 is to be estimated from dust size and density parameters.
- f. Enter items 22 through 28 for nonlinear drag model.
- g. Enter items 22 through 24 for linear drag model.
- h. Generally 20 cycles are sufficient.
- i. For tabular results specify DETAILED, SUMMARY or AVERAGE; for graphical results specify PLOT or leave blank.
- j. Enter only in special case when a_c measurement is available.
- k. Card can be left out if default values are sufficient or if no plotted output is desired.



FABRIC FILTER MODEL - DATA INPUT FORM

a}ON THE SAME CARD, ENTER ONE OR
b}THE OTHER, BUT NOT BOTH

c-REQUIRED IF K_2 IS KNOWN

d-REQUIRED IF K_2 IS TO BE CORRECTED FOR SIZE PROPERTIES

e-REQUIRED IF K_2 IS TO BE ESTIMATED

f-REQUIRED FOR NON-LINEAR DRAG MODEL

g-REQUIRED FOR LINEAR DRAG MODEL

JOB NUMBER

DATE

NAME OF PERSON COMPLETING FORM

TITLE
No. of Compartments
CLEANING TIMES
Single Compartment
Full Cycle
Time Between Cleaning Cycles a
Limiting Pressure Drop a
Reverse Flow Velocity b
SHAKING b
Freq.
Ampl.
1
2
3
4
5
6
7
8
Average Face Velocity
Gas Temp.
Inlet Dust Concentration
Measured at Temp.
9
10
11
12
K2 c,d
MEASURED AT
Temp.
Velocity
REFERENCE DUST d
MMD
σg
DUST MODELED d,e
MMD
σg
Particle Density
Bulk Density e
13
14
15
16
17
18
19
20
21
SE f
Measured at Temp
ωR f
SR f
Measured at Temp
KR f
Measured at Temp
22
23
24
25
26
27
28
MAX. No. Cycles
Accuracy Level
TYPE OF RESULTS
Tabular
Graphic
Kc
29
30
31
32
33
PLOT SIZE
X-Axis
Y-Axis
34
35

▲ = IMPLIED DECIMAL POINT.
ALL OTHER ENTRIES MUST BE RIGHT JUSTIFIED EXCEPT FOR ITEMS 0, 31 AND 32.

Figure 1. Fabric filter model - data input form.

categories: Design Data, Operating Data, Dust and Fabric Properties and Special Program Instructions. Table 2 also shows the correct units for each data input as well as the Card and Item number for entry on the Data Input Form, Figure 1. Additionally, the valid ranges; i.e., the range of numerical values that will allow the program to run, are indicated for key variables. Table 2 also indicates Default Values which are automatically assigned by the program when no data inputs are available or when the model user forgets to make an entry. In the Table 2 footnotes, those conditions defining specific or mutally exclusive data inputs are summarized. A more detailed treatment of user instructions is given in the User's Guide.[4]

Data Input Forms

The specific data inputs to be entered on each of the seven cards are listed below:

- 1 - Heading or Title Card
- 2 - Design Data
- 3 - Operating Data
- 4 - Specific Resistance Coefficient/Gas and Dust Properties
- 5 - Fabric and Dust Properties
- 6 - Special Program Instructions
- 7 - Plot (Graph) Dimensions

To facilitate data entry and subsequent card punching, a "FABRIC FILTER MODEL-DATA INPUT FORM" has been prepared, Figure 1, with the data entry locations labeled to correspond to their respective code numbers on Table 2. In those blocks where no decimal point indicator is shown, right justification of the entry is required. Some items requiring special consideration are discussed in this section. If more than one compartment is cleaned simultaneously (Item 1, Card 2) the revised or effective value for number of compartments is the total compartment number divided by the number undergoing simultaneous cleaning. Failure to enter a value for compartment cleaning time (Item 2, Card 2) will result in a DEFAULT entry. However, the program will not function if the cleaning cycle time (Item 3, Card 2) is omitted. In the case of back-to-back or continuous cleaning, Items 4 and 5, Card 2, may be left blank although a "zero" entry avoids confusion. It should also be noted that the program will function when no value or a zero value is entered for reverse flow velocity (Item 6, Card 2). The average face velocity (Item 9, Card 3) as computed from the total volume flow through the baghouse and the total available filtration area must always be entered at the actual gas stream temperature (Item 10, Card 3). In the case of K_2 estimation, DEFAULT values for temperature and velocity (Items 14 and 15, Card 4) are automatically entered. Note that if no value for K_2 is entered, the program will not function unless specific size and density parameters (Item 18 through 21, Card 4) are entered. Except for those cases where data inputs are available for the terms S_E, W_R, S_R, and K_R (Items 22, 24, 25, 27, Card 5) the program will always select the linear modeling approach. In most cases, it is advisable to select 20 operating cycles (Item 29, Card 6). With respect to accuracy code, (Item 30, Card 6) "0" and "1" entries, respectively, define convergence limits within 1 and 0.3 percent of the estimated limiting values for the key performance variables. The selection of "DETAILED" for Item 31, Card 7 provides highly specialized outputs that are only necessary for research applications. Specification of SUMMARY will furnish information on the changes in overall system effluent concentration, penetration and fabric pressure loss with time as well as average, maximum and minimum values for the above performance characteristics (the AVERAGE output). For many practical situations, selection of AVERAGE parameters is sufficient to assess compliance potential. Although the graphing capability is an extra feature, the curves produced when PLOT is specified may elimiante considerable hand plotting.

Error Messages

In accordance with good programming procedures, an attempt has been made to anticipate the major causes of computer program malfunctions, most of which relate to improper data entries. Thus, when the program fails an error message(s) will appear on a separate print-out sheet captioned DIAGNOSTIC MESSAGES. A listing of typical error messages and their probable causes and means of correction is given in Table 3. Note also that this same print-out also signifies a "go ahead" by the statement "THERE ARE NO ERRORS IN THE INPUT DATA."

EXAMPLE OF MODEL APPLICATION

The following example illustrates how the filtration model may be used by enforcement personnel to help solve a typical field problem. An electric utility operates two, coal-burning steam-electric plants, the first of which now uses a pressure-controlled baghouse to maintain particulate (fly ash) emissions at or below compliance levels. It has been proposed that a continuously cleaned fabric filter system be installed at the second plant. Both the utility operator and the local emission enforcement groups would like to determine whether operation of the new filter system in accordance with the input data shown in Table 4 will satisfy local emission requirements while maintaining average system pressure drop levels within the exhaust capacity range of the induced draft fans. For present purposes, it is assumed that operation at an efficiency of 99.5 percent (equivalent to $\underline{0.5}$ percent penetration) and an average pressure drop of $< \underline{1750}$ N/m^2 (7 in. water) indicates acceptable performance. Although a lower operating pressure loss is usually preferred, limited physical space and a desire to make use of the existing draft fans has led to the utilities acceptance of the indicated pressure drop characteristics (<1750 N/m^2).

Design and operating data appearing in Table 4 for the proposed "second" plant baghouse represent a composite of information received from both utility personnel and the dust collector manufacturer. It is also assumed that previous measurements of uncontrolled mass emission rates and fly ash size distributions at both plants are available as well as estimates for the terms K_2, S_E and W_R based upon special tests performed at the first plant. It should be noted that the above terms might have been estimated from strip chart records from the first plant showing the pressure loss versus time traces. There is the important constraint, however, that the time intervals between cleaning be long enough (∿2 hours) to develop a uniform density dust deposit on the fabric surface.

TABLE 3. SUMMARY OF DIAGNOSTIC MESSAGES AND THEIR INTERPRETATION

Message*	Probable cause/corrective measures
- ILLEGAL REQUEST FOR TYPE OF RESULTS	Incorrect spelling of DETAILED, SUMMARY, AVERAGE or PLOT for Items 31 and 32, Card 6.
- THE NUMBER OF COMPARTMENTS MUST NOT EXCEED 30	Too many compartments were entered for Item 1, Card 2.
- THE NUMBER OF COMPARTMENTS TIMES THE COMPARTMENT CLEANING TIME MUST BE LESS THAN THE CLEANING CYCLE TIME	Too many compartments, too large a compartment cleaning time or too small a cleaning cycle time were specified - Items 1, 2, and 3, Card 2.
- THE COMPARTMENT CLEANING TIME MUST BE LESS THAN THE TOTAL CYCLE TIME	Too large a compartment cleaning time, Item 2, Card 2, or too small a cleaning cycle time, Item 3, Card 2, were specified.
- TIME INCREMENT TOO SMALL, I.E., < 0.01 MINUTES	The time increment calculated by the program is too small. Too many compartments (Item 1, Card 2) or too small a cleaning cycle time, Item 3, Card 2, will cause this problem.
- AVERAGE FACE VELOCITY OUT OF RANGE, 0.3 TO 3.0	Too large or too small an average face velocity was entered for Item 9, Card 3.
- A GAS TEMPERATURE HAS NOT BEEN ENTERED	A value less than or equal to 0°C was entered for Item 10, Card 3.
- INVALID FREQUENCY OR AMPLITUDE FOR SHAKER	A > 0 value entered for either frequency, Item 7, Card 2 or amplitude, Item 8, Card 2. Both must be entered or left blank for program to operate.
- INVALID ACCURACY CODE	Only 0 and 1 are valid codes. Make certain the number is right justified when entered for Item 30, Card 6.
- BOTH TIMED AND PRESSURE CONTROLLED CLEANING SPECIFIED - ONLY ONE IS VALID	On Card 2, values for both Items 4 and 5 were entered. Only one item may be entered per test.
- PARTICLE SIZE DATA FOR K_2 ARE INCOMPLETE	A value for K_2, Item 13, Card 4, was entered along with data to be used in correcting K_2 for dust size properties, Items 16 through 19, Card 4. However, an omission from Items 16 through 19 has led to any of the following error messages.
- MASS MEDIAN DIAMETER OF MEASUREMENT OUT OF RANGE 2 TO 50	The MMD of the reference dust, Item 16, Card 4, is out of the valid range.
- THE PROGRAM HAS BEEN TERMINATED BECAUSE OF ERRORS IN THE INPUT DATA	Since one or more of the above errors has occurred, program execution is stopped. Correct the error(s) and rerun the program.
- THERE ARE NO ERRORS IN THE INPUT DATA	No errors were detected. The simulation will be performed.

*Out of order and missing cards (with the exception of Card 7) will cause many of the above errors to occur. Check card order before running program.

TABLE 4. AVAILABLE INPUT DATA FOR MODELING BAGHOUSE PERFORMANCE AT ELECTRIC UTILITY, PLANT 2

	Existing Plant A	Proposed Plant B
Number of compartments		30
Cleaning cycle duration		30 minutes
Time to clean one compartment		1 minute*
Cleaning type		Collapse/reverse air
Reverse flow volume		30,000 acfm
Cleaning cycle initiation		Continuous cleaning
Volume flow into baghouse		600,000 acfm
Total filtration area		200,000 ft^2
Temperature of flue gas		350°F
Inlet concentration		5 grains/scf
Inlet dust mass median diameter	10 μm (Reference)	7 μm
Inlet dust geometric standard deviation	3.0 (Reference)	2.5
Dust specific resistance, K_2	10.2 in.W.C.-ft-min/lb	
Measured @	500°F	
Measured @	2 ft/min	
Effective residual drag	0.636 in.W.C.-min/ft	
Measured @	500°F	
Residual fabric loading	0.015 lb/ft^2	

Note: All English units must be converted to their metric equivalents.

*Usually 2 to 3 minutes are allowed for cleaning.

The data summarized in Table 4 are sufficient to carry out the predictive modeling operation. Following transcription of the information from Table 4 into the units and format shown in Figure 2, the data inputs are ready for punch-carding.

Card 1 contains the title which will appear with the results. Note that on Card 2 the time between cleaning cycles, Item 4, and the limiting pressure, Item 5, have been left blank because a continuous cleaning system has been chosen. The reverse flow velocity, Item 6, Card 2, is calculated from the total reverse flow rate (30,000 acfm) and the cloth area per compartment (200,000 $ft^2/30$) as 4.5 ft/min or 1.37 m/min. The average face velocity, Item 9, Card 3, is computed from the indicated value for the total gas flow (600,000 acfm) and the total fabric area (200,000 ft^2) as 3.0 ft/min (0.915)m/min). Inlet concentration is reported at ambient temperature, $\sim 25^{\circ}C$, the value entered for Item 12, Card 3.

The data available for K_2 are sufficient to allow for correction of the measured K_2 at the first plant to the size properties of the dust at the second plant. Thus K_2, the temperature and face velocity at which it was measured and the size properties of the two dusts are entered as shown on Card 4. The model user should note that much of the raw field data may appear in English units, necessitating their conversion to the metric units used in the model. See Table 5

Twenty cycles are considered sufficient to complete the simulation and achieve steady state conditions (see Card 6). Similarly, an accuracy level of zero is considered acceptable for the first trial. Because the utility personnel and the enforcement agency are concerned mainly with average emission rates and average pressure drop, AVERAGE results are requested. Since no plotting is desired, Item 32, Card 7 has been left blank.

If the results of the simulation had indicated emission levels close to, but greater than, the allowable level, the simulation could bave been rerun with an accuracy level of 1. If convergence had not been reached within 20 cycles, a value of 40, for example, might have been entered provided that the costs for added computer time were acceptable.

In Table 6, the actual computer printout provided for the input data and instructions of Figure 2 have been arranged in a convenient tabulation showing each of four separate printout sheets. Printout No. 1 shows the actual summarized input data as entered into the program so that the user can check the data for errors or omissions. Printout No. 2 instructs the user via the statement "There are no errors in the input data" that the modeling program will be executed as requested. Printout No. 3 provides a listing of those parameters whose values were computed or corrected by the program such as a_c and K_2. Again, inspection of these data by the model user allows him to determine the reasonableness of the indicated values. Finally, the AVERAGE data shown in Printout No. 4 indicate that both the pressure drop and penetration expectations for the filter system (< 1750 N/m^2 and 0.5 percent) should be realized. In addition, Printout No. 4 also indicates that 10 cycles rather than the 20 requested on the data input form, were sufficient to define steady state operating conditions.

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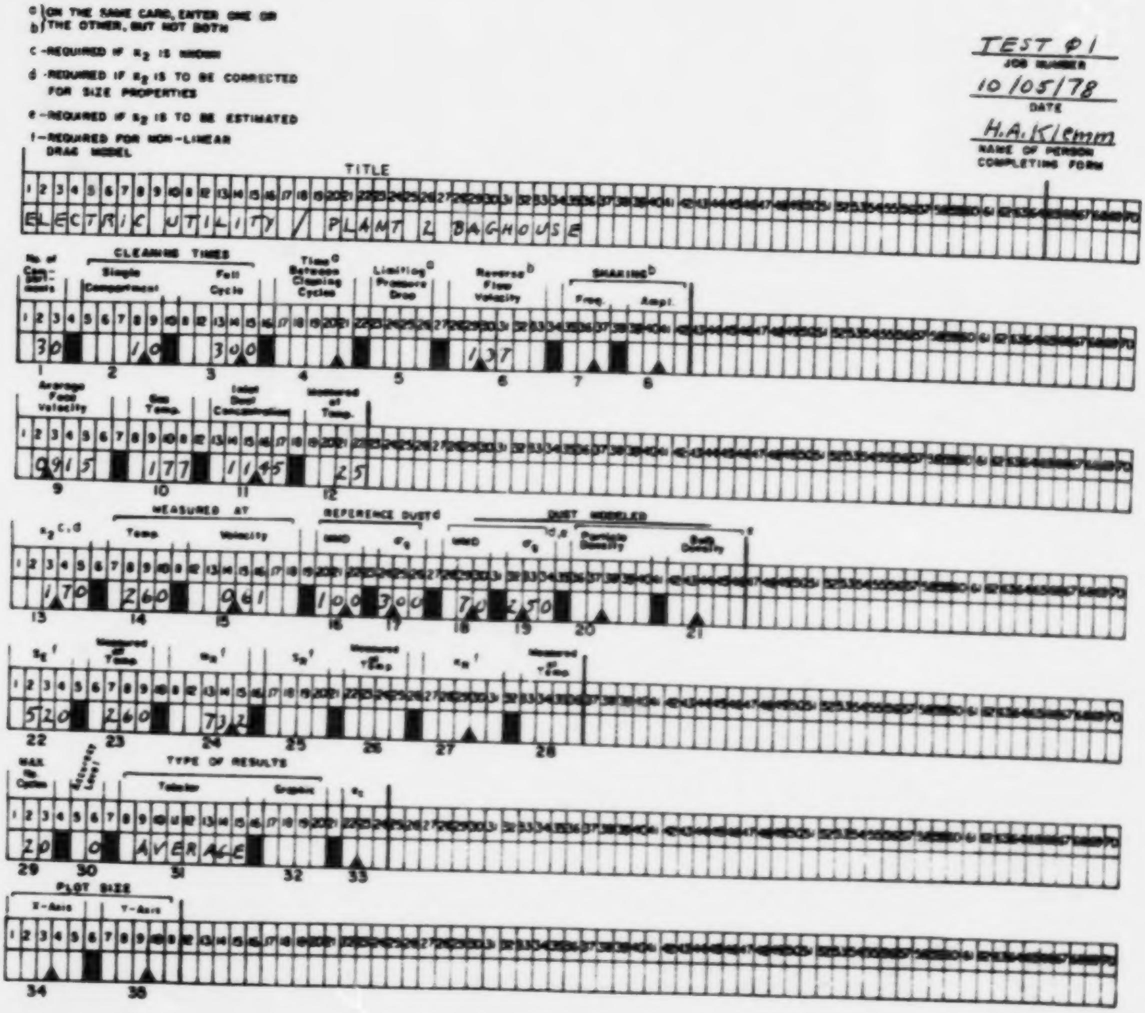

a) ON THE SAME CARD, ENTER ONE OR
b) THE OTHER, BUT NOT BOTH

c - REQUIRED IF K_2 IS KNOWN

d - REQUIRED IF K_2 IS TO BE CORRECTED FOR SIZE PROPERTIES

e - REQUIRED IF K_2 IS TO BE ESTIMATED

f - REQUIRED FOR NON-LINEAR DRAG MODEL

TEST 01
JOB NUMBER

10/05/78
DATE

H.A. Klemm
NAME OF PERSON COMPLETING FORM

TITLE: ELECTRIC UTILITY / PLANT 2 BAGHOUSE

1. No. of Compartments: 30
2. CLEANING TIMES – Single Compartment: 10
3. CLEANING TIMES – Full Cycle: 300
4. Time Between Cleaning Cycles[a]:
5. Limiting Pressure Drop[a]:
6. Reverse Flow Velocity[b]: 137
7. SHAKING[b] – Freq.:
8. SHAKING[b] – Ampl.:

9. Average Face Velocity: 0915
10. Gas Temp.: 177
11. Inlet Dust Concentration: 1145
12. Measured at Temp.: 25

13. K_2[c,d]: 170
14. MEASURED AT – Temp.: 260
15. MEASURED AT – Velocity: 061
16. REFERENCE DUST[c] – MMD: 100
17. REFERENCE DUST[c] – σ_g: 300
18. DUST MODELED[d,e] – MMD: 70
19. DUST MODELED[d,e] – σ_g: 250
20. DUST MODELED[e] – Particle Density:
21. DUST MODELED[e] – Bulk Density:

22. S_E[f]: 520
23. Measured at Temp.: 260
24. W_R[f]: 732
25. S_R[f]:
26. Measured at Temp.:
27. K_R[f]:
28. Measured at Temp.:

29. MAX No. Cycles: 20
30. Accuracy Level: 0
31. TYPE OF RESULTS – Tabular: AVERAGE
32. TYPE OF RESULTS – Graphic:
33. K_2:

PLOT SIZE
34. X-Axis:
35. Y-Axis:

Figure 2. Fabric filter model - data input form.

TABLE 5. ENGLISH/METRIC CONVERSION FACTORS

Quantity	To convert from	To	Multiply by
Filter resistance	in. H_2O	N/m^2	249
Filter drag	in. H_2O-min/ft	N-min/m^3	817
Velocity	ft/min	m/min	0.305
Volume flow	ft^3/min	m^3/min	0.0283
Fabric area	ft^2	m^2	0.093
Areal density	lb/ft^2	g/m^2	4882
Specific resistance coefficient	in.W.C.-min-ft/lb	N-min/g-m	0.167
Dust concentration	grains/ft^3	g/m^3	2.29
Density	lb/ft^3	g/cm^3	0.0160

TABLE 6. SAMPLES OF TABULAR PRINTOUT FOR EXAMPLE OF MODEL APPLICATION

PRINTOUT NO. 1

```
****************************************************************************

SUMMARY OF INPUT DATA FOR BAGHOUSE ANALYSIS

****************************************************************************

AN ELECTRIC UTILITY / PLANT B BAGHOUSE

BASIC DESIGN DATA
     NUMBER OF COMPARTMENTS            30
     COMPARTMENT CLEANING TIME          1.0          MINUTES
       (OFF LINE TIME)
     CLEANING CYCLE TIME               30.0          MINUTES
     CONTINUOUSLY CLEANED SYSTEM
     REVERSE FLOW VELOCITY              1.3725       M/MIN



OPERATING DATA
     AVERAGE FACE VELOCITY             0.9150        M/MIN
     GAS TEMPERATURE                   177.          DEGREES CENTIGRADE
     INLET DUST CONCENTRATION          11.45         G/M3
          MEASURED AT                   25.          DEGREES CENTIGRADE
FABRIC AND DUST PROPERTIES

     SPECIFIC RESISTANCE, K2            1.70         N-MIN/G-M
          MEASURED AT                  260.          DEGREES CENTIGRADE
                                       0.6100        M/MIN
                         MMD1         10.0           MICRONS       -STANDARD DEVIATION 3.00
          CORRECTED TO   MMD2          7.0           MICRONS       -STANDARD DEVIATION 2.50
     EFFECTIVE RESIDUAL DRAG, SE      520.           N-MIN/M3
          MEASURED AT                 260.           DEGREES CENTIGRADE
     RESIDUAL LOADING, WR              73.2          G/M2

SPECIAL PROGRAM INSTRUCTIONS
     MAX NUMBER OF CYCLES MODELED     20
     ACCURACY LEVEL                   0
     TYPE OF RESULTS REQUESTED        AVERAGE /
```

PRINTOUT NO. 2

```
DIAGNOSTIC MESSAGES


THERE ARE NO ERRORS IN THE INPUT DATA
```

(continued)

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TABLE 6. (continued).

PRINTOUT NO. 3

```
CALCULATED VALUES


INLET DUST CONCENTRATION                         7.58          G/M3
CORRECTED TO OPERATING TEMPERATURE

FABRIC AND DUST CAKE PROPERTIES CORRECTED FOR GAS VISCOSITY

     SPECIFIC CAKE RESISTANCE, K2          2.14          N-MIN/G-M

     EFFECTIVE DRAG, SE                   620.           N-MIN/M3

FRACTIONAL AREA CLEANED, AC           0.27

TIME INCREMENT                             0.25          MINUTES

SYSTEM CONSTANT **                          0.0          G/M2
```

PRINTOUT NO. 4

```
              ********************************************************************************

              RESULTS OF BAGHOUSE ANALYSIS

              ********************************************************************************

              AN ELECTRIC UTILITY / PLANT H BAGHOUSE


FOR      30.00 MINUTES OPERATION,  CYCLE NUMBER   8
                                                  AVERAGE PENETRATION=              3.33E-03
                                                  AVERAGE PRESSURE DROP=              1558.78 N/M2
                                                  AVERAGE SYSTEM FLOW=                 0.9607 M/MIN
                                                  MAXIMUM PENETRATION=              4.75E-03
                                                  MAXIMUM PRESSURE DROP=              1576.12 N/M2

FOR      30.00 MINUTES OPERATION,  CYCLE NUMBER   9
                                                  AVERAGE PENETRATION=              3.33E-03
                                                  AVERAGE PRESSURE DROP=              1558.04 N/M2
                                                  AVERAGE SYSTEM FLOW=                 0.9607 M/MIN
                                                  MAXIMUM PENETRATION=              4.74E-03
                                                  MAXIMUM PRESSURE DROP=              1574.95 N/M2

FOR      30.00 MINUTES OPERATION,  CYCLE NUMBER  10
                                                  AVERAGE PENETRATION=              3.33E-03
                                                  AVERAGE PRESSURE DROP=              1557.74 N/M2
                                                  AVERAGE SYSTEM FLOW=                 0.9607 M/MIN
                                                  MAXIMUM PENETRATION=              4.74E-03
                                                  MAXIMUM PRESSURE DROP=              1574.50 N/M2
```

SUMMARY

The primary purpose of this paper has been to highlight the developmental aspects of the filtration model that have been described in detail in precursor studies and to show precisely how the model can be used to estimate the performance of a new filter system while design and operating parameters are still open to change. The example chosen to illustrate the model application indicates that a basic understanding of filtration concepts with concurrent definition of key input parameters enables the model user to obtain a simple answer as to the probable success of the filter system design undergoing evaluation.

ACKNOWLEDGMENTS

The authors express their appreciation to Dr. James H. Turner, EPA Project Officer, for his continued technical support throughout the programs under which the present filtration model has been developed.

This project has been funded at least in part with Federal funds from the Environmental Protection Agency under contract number 68-02-1438, Task Order Nos. 5, 6 and 7, and contract number 68-02-2607, Task Order Nos. 7 and 8. The contents of this publication do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency, nor does mention of trade names, commercial products, or organizations imply endorsement by the U.S. Government.

REFERENCES

1. Dennis, R., et. al. Filtration Model for Coal Fly Ash with Glass Fabrics. U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina. EPA-600/7-77-084. August 1977.

2. Dennis, R., R. W. Cass, and R. R. Hall. Dust Dislodgement From Woven Fabrics Versus Filter Performance. J Air Pollut Control Assoc. 48 No. 1, 47-52, 1978.

3. Dennis, R., and N. F. Surprenant. Particulate Control Highlights: Research on Fabric Filtration Technology. U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina. EPA-600/8-78-005d. June 1978.

4. Dennis, R. and H. A. Klemm. Fabric Filter Model Format Change. Vol. I Detailed Technical Report, Vol. II User's Guide. U.S. Enivronmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina. EPA-600/7-79-043a, EPA-600/7-79-043b. February 1979.

5. Dennis, R. and H. A. Klemm. A Model for Coal Fly Ash Filtration. J Air Pollut Control Assoc. 49 No. 3,230-234, 1979.

6. Dennis, R., H. A. Klemm and W. Battye. Fabric Filter Sensitivity Analysis. U.S. Enivronmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina. EPA-600/7-79-043c. April 1979.

7. Dennis, R., and J. E. Wilder. Fabric Filter Cleaning Studies. U.S. Environmental Protection Agency, Control Systems Laboratory, Research Triangle Park, North Carolina. EPA-650/2-75-009 (NTIS No. PB-240-372-3G1). January 1975.

8. Billings, C. E., and J. E. Wilder. Handbook of Fabric Filter Technology, Volume I, Fabric Filter Systems Study, 1970. U.S. Environmental Protection Agency, Control Systems Laboratory, Research Triangle Park, North Carolina. EPA-APTD 0690 (NTIS No. PB-200-648). December 1970.

9. Leith, D. H., M. W. First and H. Feldman. Performance of a Pulse-Jet Filter at High Filtration Velocity - II. Filter Cake Redeposition, J. Air Pollut Control Assoc. 27 No. 7, 636-640, 1977.

10. Ellenbecker, M. J., and D. Leith. Effect of Dust Cake Redeposition on Pressure Drop in Pulse-Jet Fabric Filters. Paper Presented at 3rd International Powder & Bulk Solids Handling & Processing Conference, Rosemont, Ill., May 1978.

11. Dennis, R. and H. A. Klemm. A System Model for Pulse-Jet Filtration. Publication pending editorial review. 1979.

PARTICULATE REMOVAL AND OPACITY USING A WET VENTURI SCRUBBER - THE MINNESOTA POWER AND LIGHT EXPERIENCE

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Minnesota Power and Light is installing a wet venturi particulate scrubber and a spray tower SO_2 absorber as the Air Quality Control System for their 500MW Unit #4, Clay Boswell Station, Cohasset, Minnesota. The System is being designed and installed by Peabody Process Systems, Inc., Stamford, Connecticut.

Prior to start-up the full scale unit, a 1MW pilot plant was installed and tested to evaluate the performance of the system. Estensive data was collected for two different western coals with regard to venturi particulate removal characteristics and its effect on opacity. Correlations were also developed using pilot plant opacity data to predict full scale opacity results.

This paper summarizes the test results obtained and conclusions reached.

PARTICULATE REMOVAL AND OPACITY USING A WET VENTURI SCRUBBER- THE MINNESOTA POWER AND LIGHT EXPERIENCE

1. INTRODUCTION

Minnesota Power & Light is currently expanding its power generating capacity at its Clay-Boswell station, Cohasset, Minnesota by the addition of Unit #4 with a capacity of 500 MW. The Air Quality Control System this unit was designed and installed by Peabody Process Systems, Stamford, Conn., and consisit of an integral venturi particulate scrubber and a spray tower SO_2 absorber... The system is designed for 99.7% particulate removal and 90% SO_2 removal based upon burning a sub-bituminous coal from the "Big Sky" mine at Colstrip, Montana where the Rosebud and McKay seams vary in sulfur content from 0.4% to 2.8% with about 10% ash content.

The initial design of the plant called for a hot-side or cold-side electrostatic precipitator followed by a spray tower SO_2 absorber. However, when Minnesota Power & Light solicited bids on this basis, the quoted costs appeared to be very high. In addition, Minnesota Power & Light had some doubts that the precipitator could meet the stringent performance required for their system. Likewise, it was also known that the alkali contained in the flyash could offer economic benefits in SO_2 removal.These factors led Minnesota Power & Light to explore the concept of using a wet venturi for particulate removal and integrating it with the SO_2 spray tower absorber.

2. ECONOMIC EVALUATION

Three alternate systems were evaluated by Minnesota Power & Light. They were:

System #1:	Hot-side electrostatic precipitator followed by an SO_2 absorber. Reheat by means of a 5% hot flue gas bypass which is treated for particulate removal via a small hot-side electrostatic precipitator.
System #2:	Cold-side electrostatic precipitator followed by an SO_2 absorber. Reheat by means of a 5% flue gas bypass which is treated for particulate removal via a small hot-side electrostatic precipitator.
System #3:	Venturi scrubber followed by an SO_2 absorber. Reheat by means of a 5% flue gas bypass which

is treated for particulate removal via a small hot-side electrostatic precipitator.

The economic evaluation, based upon actual bids received, included investment, operating and maintenance costs for the three systems. Special emphasis was placed on determining the availability of these systems and the risk factors associated with each.

The total investment for each system, including necessary sub-systems (e.g., waste disposal for ash and scrubber sludge; induced fans; and air preheaters), is tabulated below in thousands of dollars:

	System 1	System 2	System 3
INVESTMENT	73,939	81,091	53,279
DIFFERENTIAL	20,660	27,812	BASE

The following table summarizes annual owning and operating costs in thousands of dollars:

	System 1	System 2	System 3
FIXED CHARGES	12,570	13,785	9,057
CAPABILITY CHARGE	1,335	1,563	1,606
REAGENT & UTILITIES	4,129	3,781	3,307
OPERATING & MAINTENANCE	5,096	51,77	6,083
TOTAL ANNUAL CHARGES	23,130	24,306	20,053
DIFFERENTIAL	3,079	4,253	BASE
PRESENT WORTH - 30 YEARS	193,000	203,014	167,505
DIFFERENTIAL	25,696	35,509	BASE

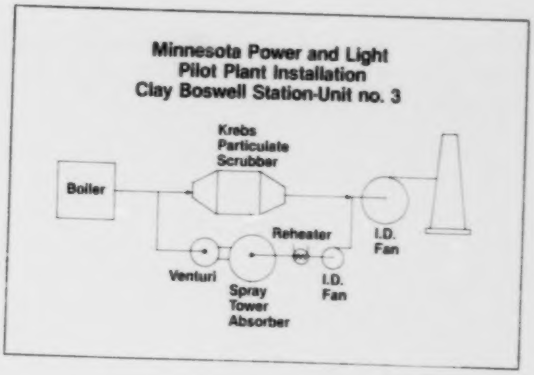
The conclusions of the economic analysis are self-evident. System 3---is a great deal lower in installed cost, but operating and maintenance costs are only slightly greater than the ESP/spray tower systems. The net result is that the integral venturi/spray tower absorber system is the most economical method of achieving Minnesota Power & Light's air quality control requirements.

3. DESCRIPTION OF PILOT PLANT AND TEST OBJECTIVES

In November 1977, Minnesota Power & Light awarded a contract to Peabody Process Systems, Inc., Stamford, Conn. for the design and installation of an Air Quality Control System (AQCS) based upon using the venturi for particulate removal and a spray tower absorber for SO_2 removal. As part of its contractual commitment, Peabody offered guarantees with regard to both particulate and SO_2 removal. To confirm these guarantees and to further Minnesota Power & Light's understanding of the operating characteristics of the system which they purchased, Peabody was authorized to design, install and supervise a pilot plant test program for the evaluation of the system. This test program covered an 18 month period and involved a cost of approximately two million dollars. The objectives of this pilot plant included the following:

1. Confirm the pressure drop in the venturi required to meet particulate and opacity emission standards.
2. Confirm that the system can remove 90% SO_2 when burning coals containing up to 2.8% sulfur.
3. Demonstrate that the system can operate on a closed loop water balance.
4. Determine the alkali utilization of the flyash.
5. Evaluate alternative alkalis.
6. Define waste solids characteristics such as settling rates, percent moisture and settled solids, etc.

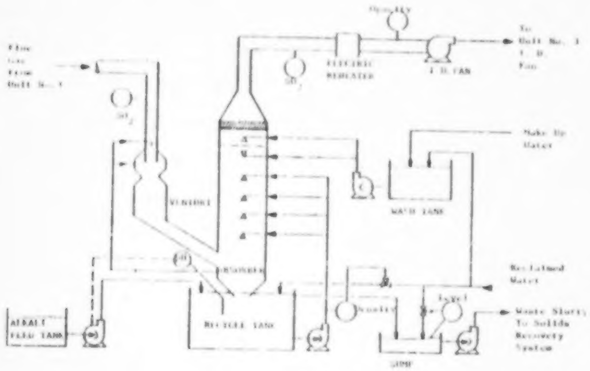
The pilot plant installed to achieve the above objectives was installed at the Clay-Boswell station taking the flue gas from Unit #3. Unit #3 has the same boiler design and is burning the same coals which are to be burned in Unit #4. Thus, the results obtained from the pilot plant could be considered representative of the results to be expected for Unit #4.



Minnesota Power and Light
Pilot Plant Installation
Clay Boswell Station-Unit no. 3

The pilot plant system was identical in concept to proposed full scale unit with some modifications based on practical considerations. The lime slakers system was not installed. An in line electric reheater was used in lieu of the hot gas bypass system. A thickener and vacuum filter was used in lieu of a waste solids pond system.

The pilot plant was designed to treat 3200 ACFM of gas. The flue gas is taken from Unit #3 ahead of an existing particulate scrubbing system and contacted in the venturi with slurry for removal of the particulate matter. This slurry is the same material used for absorbtion of SO_2. The gas and slurry leaving the venturi flows to the base of the spray tower absorber where the gas and slurry separate. The slurry drains to the recycle tank, the gas flows upward through the spray tower absorber where it is further contacted with recirculated slurry which is pumped through multiple spray headers to achieve the desired degree of SO_2 removal. The clean gas prior to leaving the absorber flows through a mist eliminator section consisting of an interface tray and chevron mist eliminator. After leaving the absorber, the gas is reheated by an in-line electric heater. The reheated gas then goes through an I.D. fan and is reintroduced into the suction of the I.D. fan for Unit #3. The pilot plant also contains an alkali feed tank from which alkali is fed to maintain the desired slurry pH, a supplemental flyash feeding system and a thickener and vacuum filter for treatment of waste solids. Particular attention was given to the quality of instrumentation to insure reliability of the pilot plant operation and test results. Inlet and outlet SO_2 concentrations were continuously monitored by means of SO_2 analyzers. A nuclear density device was maintaining the slurry concentration. Automatic pH control and an optical opacity meter were also provided with the system.



Venturi Design

The venturi selected for particulate removal is based upon the radial flow design concept. The design of a venturi must contend with the problems of abrasion and also solids build up due to hot gas contacting the slurry used for particulate removal. To avoid solids build up, the venturi is designed using a "dentist bowl" concept. The upper section of the venturi consists of a conical section in which slurry is introduced tangentially. The quantity of slurry used is several times greater than the potential evaporative capacity of the hot flue gas. The excess quantity of the tangentiable flows of the slurry insures that the conical section is completely wetted. The hot flue gas enters the venturi through an insulated thimble section which introduces the gas below the slurry injection point and this keeps the gas slurry contact point below the wet-dry line and avoids solid build up.

Abrasion can occur in three distinct areas of the venturi. The first is where the gas makes a 90° turn to flow through the cylindrical orifice. Abrasion in this area is avoided by having the gas impinge on a pan filled with slurry, which absorbs the impact of the gas. This pan is maintained full by the flow of slurry from the "dentist bowl" and supplemental slurry added via a bull nozzle.

The slurry overflow from the pan and the gas are then mixed intimately in the cylindrical orifice around the pan. It is at this point that particulate removal is achieved. Abrasion is also a factor at the orifice which cannot be eliminated. However, the wear surface in the orifice area is fabricated from disposible angle iron sections which provided for simplified maintenance.

The gas and slurry mixture leaving the orifice area has a high velocity which if allowed to impact on a surface, could also cause severe abrasion problems. This situation is avoided by maintaining a sufficient distance between the orifice area and the wall of the venturi. This allows the gas to expand and slow down sufficiently to be nonabrasive. As an added precaution the wall is rubber lined to withstand any residual abrasive impact.

Thus of the three intended abrasive cases, two have been eliminated and the third one minimized by providing a design for simplified replacement. The radial flow venturi design is a balance force system since the gas velocity is equal in the 360° lateral plane circumference of the orifice. The force exerted on the mechanical operator due to the venturi pressure drop therefore becomes zero. This balanced design will minimize maintenance problems and is a key design feature in the reliable operation of the venturi.

The design concepts discussed above are those used for the full scale system as well as the pilot plant test program.

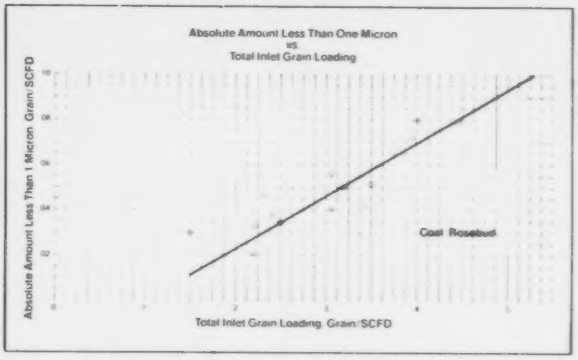
All of the objectives of the test program were achieved. However, only the results pertinent to particulate removal and opacity will be discussed in this paper.

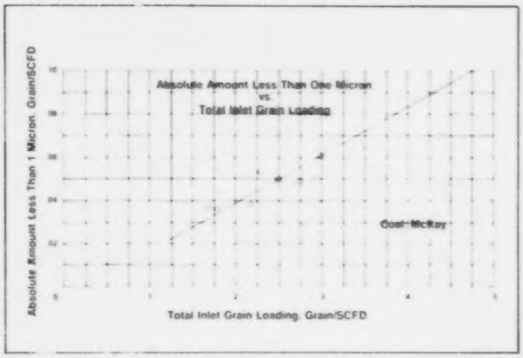
4. CHARACTERIZATION OF FLYASH PARTICLE SIZE

The flue gas duct to the pilot plant had a 14" diameter. The Unit #3 duct from which the flue gas was to be sampled has a dimension of approximately 10 feet high x 146 feet wide. From previous testing that the Minnesota Power & Light performed it was known that some segregation of the flyash occured in the section of ductwork where the flue gas was to be sampled. As a result, there was a concern that the flue gas to the pilot plant would not be representative with regard to both total grain loading and particle size distribution. Prior to locating the pilot plant test port connection in the Unit #3 duct, extensive work was done to characterize the particulates in the cross section of the Unit #3 duct. Based upon this data, a test port was selected with two alternates provided should later results dictate changing the test port. After the installation of the pilot plant, repeated particulate analyses were made of the flue gas flowing to the pilot plant and simultaneously the flue gas from Unit #3. The comparison showed that a proper sampling port had been selected and the flue gas to the pilot plant was representative of that obtained from the full scale unit.

For particle size distribution data, EPA method 5 was used. However, the method was modified by the use of an Anderson Impactor. This device allows measurement of both total grain loading and particle size distribution down to 0.3 microns. The standard EPA method 5 was also used as a check against the modified method. There was good agreement between the two methods.

At the start of the project there was some question as to how the size distribution varied with total grain loading. Some theories were expounded that the absolute quantity of fines would be a constant and that higher grain loadings would be the result of greater quantities of larger particles. The work done in characterizing both Rosebud and McKay coals demonstrated that the size distribution remains approximately constant under varying total grain loadings. When the absolute quantity of submicron material was plotted against the total grain loading in the raw flue gas a linear relationship existed for both Rosebud and McKay coals. However, the McKay coals had a greater percentage of submicron material.

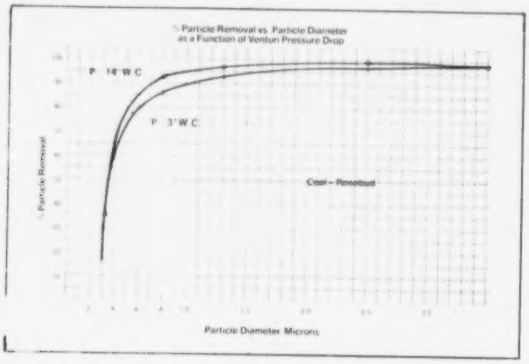




5. PARTICULATE REMOVAL

Having characterized the size distribution of the two coals tested, the effect of venturi pressure drop was evaluated with regard to percent particulate removal. For a given test condition, simultaneous particulate measurements were made of the inlet and outlet flue gasses. Again the Anderson Impactor was used to that the removal efficiency as a function of particle size could be determined. Data for the Rosebud and McKay coals were established for venturi pressure drops ranging from 6" to 31" w.c.

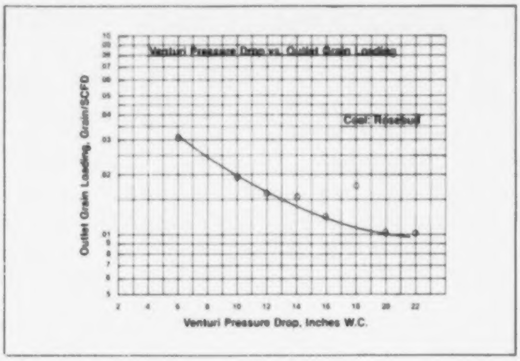
The percent removal of various particle sizes for different venturi pressure drop was plotted for both coals. The curves all follow the same trend for both different pressure drops and different coals. A typical set of curves is shown below.

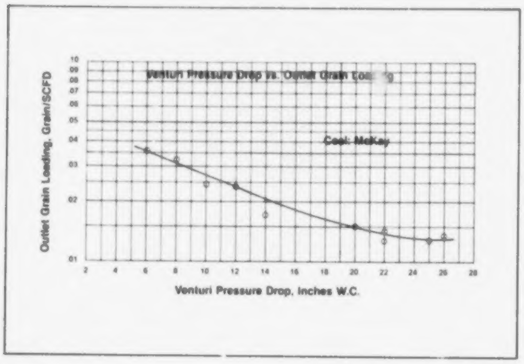


For particle sizes of 2.5 microns or larger, the percent removed is essentially 100%, regardless of venturi pressure drop. The percent removed drops off slightly as particle size decreases from 2.5 microns to 0.8 microns. It is in the less than 0.8 micron size that the venturi pressure drop has the greatest significance.

For a given venturi pressure drop, a comparison of the two coals showed that a greater percentage removal of submicron particles for McKay coal was achieved as compared to the Rosebud coal. This higher removal efficiency partically offsets the higher quantity of submicron particles in the McKay coal.

Data was also plotted showing the total outlet grain loading as a function of venturi pressure drop. The curves for both coals are shown. The economics the venturi system had been based upon achieving a 0.03 gr./SCFD (0.06 lbs/MM BTU) using a 12" w.c. pressure drop. The curves show that with Rosebud coal the 0.03 gr/SCFD could be achieved with a 6" w.c. drop pressure, whereas the McKay coal required a 8" w.c. pressure drop. Both curves appear to indicate that regardless of pressure drop, outlet grain loadings significantly less than 0.01 gr./SCFD (0.02 lbs/MM BTU) is not achievable.

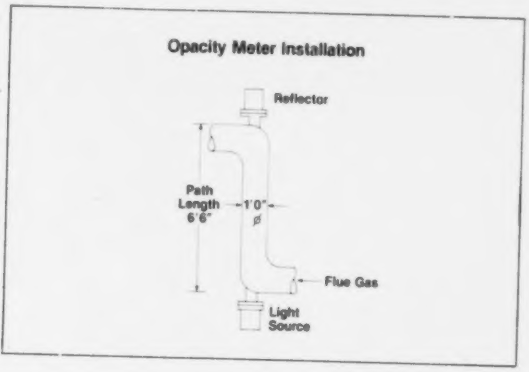




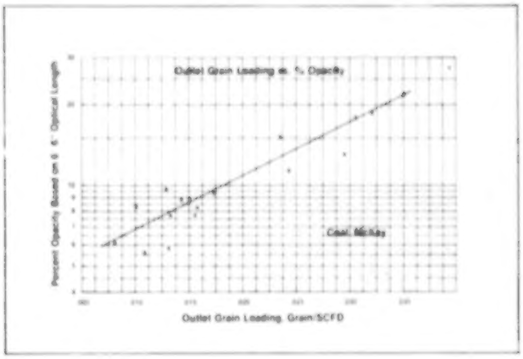
6. OPACITY

In addition to meeting particulate emission standards, a flue gas stack opacity of 20% was also established as a performance criteria. It was known that the type of coal burned significantly effected opacity results. Therefore, Minnesota Power & Light wanted a means of predicting stack opacity as a function of both venturi performance and type of coal being burned. To achieve this objective, techniques were devised for measuring opacity in the pilot plant tnd then extrapolating the data to the full scale system.

To obtain pilot plant opacity data a Lear Siegler RM41 opacity instrument was used. The opacity instrument was located down stream of the venturi and absorber system and thus, reflected total system performance. Initially the unit was installed with the light beam traversing the diameter of the 12" gas duct. After limited experience with this installation it became apparent that the margin for error with this small a path length was too great. Consequently, a second installation was made in which the path length was increased to 6'6". To achieve this path length the unit was installed between two elbows in which the larger path was parallel to the gas flow. The installation is shown below.



Venturi performance was varied to allow various outlet grain loadings to exist and thus permit measuring opacity over a range of grain loadings. Data was collected for both Rosebud and McKay coals. A semi-log plot of percent opacity vs. grain loading resulted in a straight line. When comparing opacity data for the two different coals it can be seen that the slope of the lines are different.


Outlet Grain Loading vs. % Opacity
Percent Opacity Based on 0.6' Optical Length
20
10
Coal, McKay
Outlet Grain Loading, Grain/SCFD

For a grain loading of 0.03 gr./SCF, the Rosebud coal would produce the higher percent opacity. For grain loading of 0.01 gr/SCF or less the McKay coal would produce the higher opacity value

Opacity as a function of venturi pressure drop was also correlated for each coal. As might be expected, the curves which result are consistent with the particulate removal curves. As the pressure drop increases, the opacity achieved approaches a limiting value. Consistent with the other opacity curves, at the expected venturi pressure drop of 12" w.c. which was required to meet particualate emission standards Rosebud coal has the lower percent opacity.

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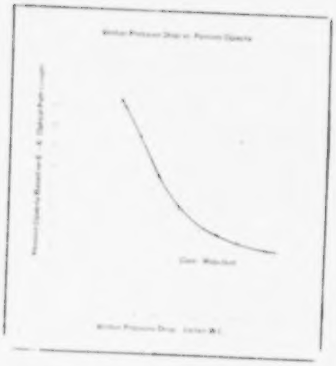
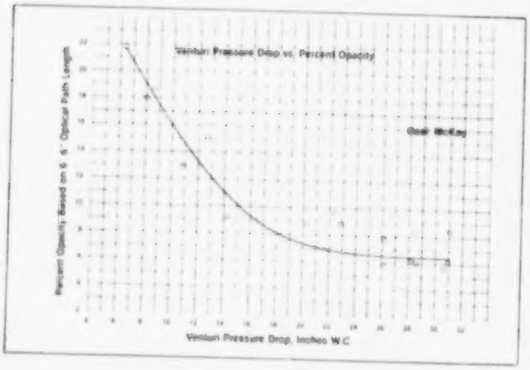




Having measured opacity in the pilot plant, the question still remained as to how to scale up the data for Unit #4 to the stack tip diameter of 35 feet. A correlation between particulate grain loadings and opacity has been shown to be as follows:

1. $W=\frac{K\rho \ln(I/Io)}{D}$ Formula from paper by D.S. Ensor and MN.J. Pilot - U. of Washington APCA Journal, Vol. 21, No. 8, August 1971.

W= Total Particulate Mass Concentration in Effluent
K= Specific Particulate Constant
p= Density of Particulate
I= Intensity of Transmitted Light
Io= Intensity of Incident Light
D= Illumination Path Length of Diameter of Plume
I/Io= Light Transmittance

On the assumption that the particulate characteristics in the pilot plant are identical to those in the full scale system the following relations were developed:

$$\log (100-O_s) = \log (100\ O_p) \times \frac{D_s}{D_p}$$

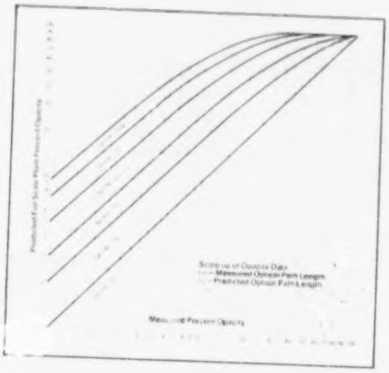
where: O_p = percent opacity measured in the pilot plant.

O_s = predicted percent Opacity in the Unit #4 stack.

D_p = pilot plant optical path length.

D_s = optical path length in the Unit #4 stack.

Using this relationship a 04.1% opacity reading in the pilot plant would be equal to a 20% opacity in the stack. This opacity relationship when plotted is shown below:



This curve highlights the significance of stack geometry in determining the measured opacity. The conclusion that can be reached is that as stack diameter is increased, the flue gas particulate loading would have to be significantly decreased to achieve desired opacity value.

At the required design particulate emissions level of 0.03 gr/SCF (0.06 lbs/MM BTU), the opacity for Rosebud coal would be 75% as opposed to 64% for McKay coal. The lowest measured pilot plant opacity reading obtained was 6% for either coal burned. To achieve this minimum opacity value, particulate emissions of 0.01 gr/SCF (0.02 lbs/MM BTU) or lower were required. When scaled up to Unit #4, this 6% pilot plant opacity value is equivalent to a 28% stack opacity. Thus is appears that for Minnesota Power & Light's situation, a 20% stack opacity is not achievable.

7. CONCLUSION

The Minnesota Power & Light experience has shown that:

a. A venturi for particulate removal can offer significant economic savings.

b. The pilot plant data confirmed that the required particulate emission standards can be met.

c. The pilot plant data indicated that for Clay Boswell Station Unit #4 particulate emission standards and opacity requirements are not consistent. Even when particulate emission standards are far exceeded, a 20% stack opacity is not achievable.

"PERFORMANCE OF ENVIROMENTALLY APPROVED NLA SCRUBBER FOR SO_2"

By:

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ABSTRACT

This paper describes the commercial development and operation of the NLA - Lewis scrubber for flue gas. The scrubber was installed on three coal fired boilers at Pfizer's chemical plant in East St. Louis, Illinois. Total operating cost, including depreciation, is budgeted at \$0.90/MM BTU. Further improvements have reduced this to \$0.60. On stream time averaged 94% the first year of full operation. Both SO_2 and particulates are within legal limits.

INTRODUCTION

The subject of this paper is the technical success of a gas absorption unit with impingement and condensation particulate collection.

But more importantly it is a success story of our present regulated technostructure.

This is a young nation. We have a strong spirit of economic progress. As a result, we have produced a record of major contributions to the health and welfare of this country and the world. Classical economics has produced much human progress and well-being.

Yet, as a nation, we have a limited sense of history and future; of tradition and culture. We depend on classical economic motivations to provide our direction.

However, classical economics alone cannot provide motivations for controlling the aggregate, long-term or probabalistic side effects of economic progress.

Therefore, we have asked our government to place constraints on the side effects of this progress.

One major side effect is aggregate air pollution. My car, my stack, by itself, has no effect on my well being or that of the community. But our cars - our stacks, together, do!

This paper is a case study of a chemical plant which installed a stack gas scrubber for purely classical economic reasons - we wanted to stay in business - legally. And, we wished to do so at the least expenditure of resources - both present and future.

Therefore, what will be presented today is primarily development history and final results, with a limited amount of technical data.

Most of the papers of this conference are research oriented. This paper is user oriented.

The net result is this: A 140,000 lb/hr. steam boiler system firing 3.5% sulfur coal that meets SO_2 and particulate standards while burning high sulfur coal, for a total add'l cost, including depreciation of less than 90¢/MM BTU.

THE PROBLEM

Pfizer's plant in East St. Louis, Ill., produces iron oxide pigments for end use products such as colorants and magnetic tape. It is the largest plant in the MPM division. This plant has three coal fired boilers, (see table 1), with a total rated output of 140,000 lb/hr. of steam. All three boilers were designed to burn high sulfur coal (4%) from the local Illinois #6 seam.

TABLE 1
BOILERS

HEAT INPUT MM BTU/HR	STEAM PRODUCED M LBS/HR	TYPE	MANUFACTURER
150	100	SPREADER	ERIE CITY
50	30	TRAVELING GRATE	B&W
20	10	TRAVELING GRATE	O'BRIEN

The Illinois high sulfur coal (table 2) is purchased from any of four or more mines (both strip and underground) within 75 miles of the plant. Both price and availability are extremely favorable when compared to alternate fuels.

TABLE 2
COAL TYPE

SULFUR	3.5%
ASH	10.0%
HEAT CONTENT	11,000 BTU/LB.
WASHED SIZE	1 1/4 X 0

However, when burning this fuel the boilers did not meet the allowable emission standards for either SO_2 or particulates. (tables 3&4)

TABLE 3
SO_2 EMISSIONS

NATURAL	1408
ALLOWED	396
REMOVAL EFFECIENCY REQUIRED	72%

TABLE 4
PARTICULATE EMISSIONS

NATURAL	145
ALLOWED	49
REMOVAL EFFECIENCY REQUIRED	66%

SOLUTIONS

We therefore had three alternates: Switch fuels, stack gas treatment or do nothing.

In a country based on law, we cannot pick and choose those we wish to obey - so that rules out alternate three, unless we cease operation.

The remaining alternates are strictly an economic choice. We chose the stack gas treatment route as being inherently more economical and, long term, more reliable than dependence on oil and gas. Yet, we wished to minimize the commitment of technical resources.

We wish to concentrate our technical resources on iron oxide, not pollution control. We needed a device that had the following characteristics:

Reliability - Higher than the boilers
Reasonable Cost - Low enough to still be more economical than alternate fuels.
Enviromentally sound - Not create new problems
Compatible with boiler operation - Should not require more complexity.

There are many types of FGD systems presently in some phase of development or operation. Due to political and economic considerations, the relative reliabilities and costs are difficult to obtain on a comparable basis. However, the following qualitative evaluation is accepted.

1.) Throw away systems (those that produce a sulfate or sulfite solid waste) are presently the most satisfactory.

2.) Calcium based systems, such as lime, are inherently simple and use inexpensive raw materials. However, the plugging characteristic of lime requires more complex systems and reduces reliability.

3.) Sodium based systems, such as double aklali, seem to be impractical for large facilities. For smaller facilities, they are in use, but add the operational and maintainance complexity of a major chemical plant; also, chemical costs can be quite high.

Of course, all the systems must have sludge separation and disposal systems. Some of these can be quite massive due to the large quantity of water required for the scrubber to prevent plugging.

THE SELECTION

We believe the scrubber we are about to describe is a reasonable answer to many of these difficulties.

- It inherently resists plugging
- It is simple to operate
- It uses very little water, so no water recycle is required
- And, of course, it uses an inexpensive reagent - Lime

The simplicity is the most important feature for us at East St. Louis, Ill. It can be operated by existing boiler house personnel with very little additional training. It can be maintained with existing shop personnel with no additional training. The flow chart is simple.

So, what is this magic device?

Very simple - a kiln.

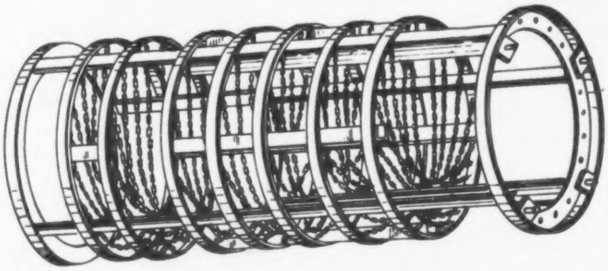
In 1974, through Mr. Wayne McCoy's membership on the Clean Air Committee of the Nat'l. Lime Assn., Pfizer at East St. Louis became aware of the development of Mr. Clifford Lewis. Mr. Lewis is a consultant to the National Lime Association and, as such, had developed a stack gas scrubber that,

a.) Used lime/limestone manufacturing technology and
b.) Used lime as the scrubbing reagent. Pfizer, through its membership in the Nat'l. Lime Association, had access to Mr. Lewis's work and rights to the ultimate patent as well.

The basic concept of Mr. Lewis's device is similar to most scrubbing systems. The flue gas is contacted with an aqueous aklaline material to remove SO_2 by absorption and subsequent precipitation; particulates are captured by impingment and condensation agglomeration. In the NLA - Lewis scrubber, (see figure 1) flue gases pass through a rotating kiln - a cylindrical shell sloped about 1/8"/ft. to provide gravity flow of the lime slurry scrubbing liquid. The apparatus contains rings of lifter boxes and great quantities of loosely hung chain. A circular dam confines a lime slurry pool through which the lifter boxes pass as the shell rotates. In this way, lime slurry is lifted and poured over the chains, providing wetted chain surface for contact with the flue gas. Internal pumping rate in our particular unit is about 5000 GPM. The loosely hung chain also scours the internal scrubber surfaces to prevent plugging.

FIGURE 1
SCRUBBER CONCEPT

U.S. Patent Nov. 29, 1977 **4,060,587**



We will now review the developmental history of this device at the East St. Louis plant.

PFIZER'S SCRUBBER

In 1975 Pfizer installed at 87-foot kiln, 11-foot diameter and fitted it with a modified NLA - Lewis chain system. (figure 2&3) In addition, Pfizer Incorporated our own design concept of a drying zone contiguous to and down stream of the wet scrubber section to dewater the waste sludge by contacting it with the incoming hot flue gases. This offers a dry waste product suitable for landfill with reduced disposal costs. It was installed as shown to handle flue gas from the large boiler only.

FIGURE 2
PFIZER SCRUBBER-1975 ORIGINAL

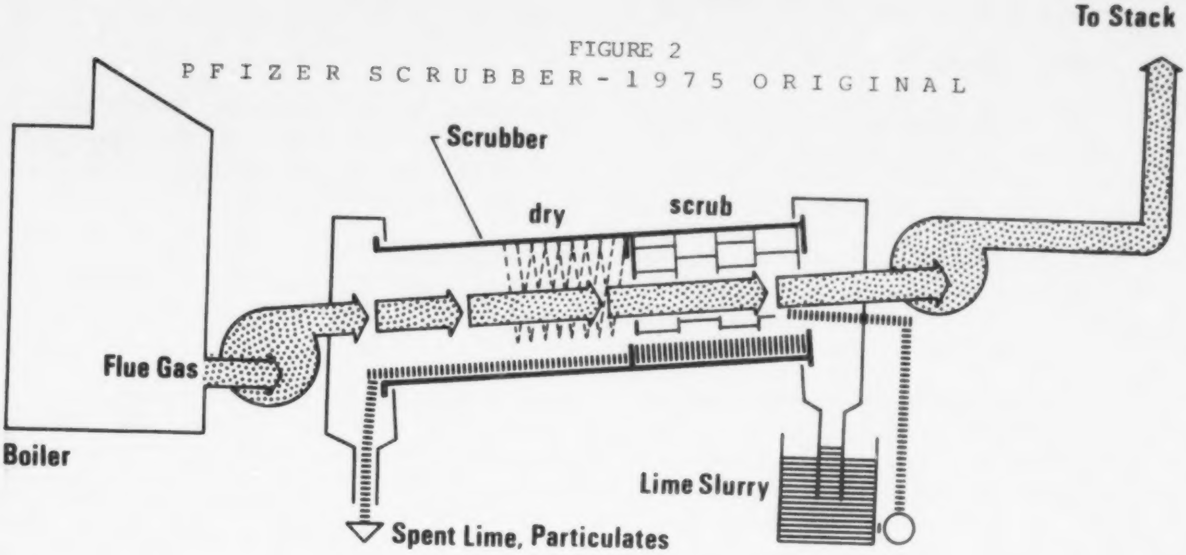
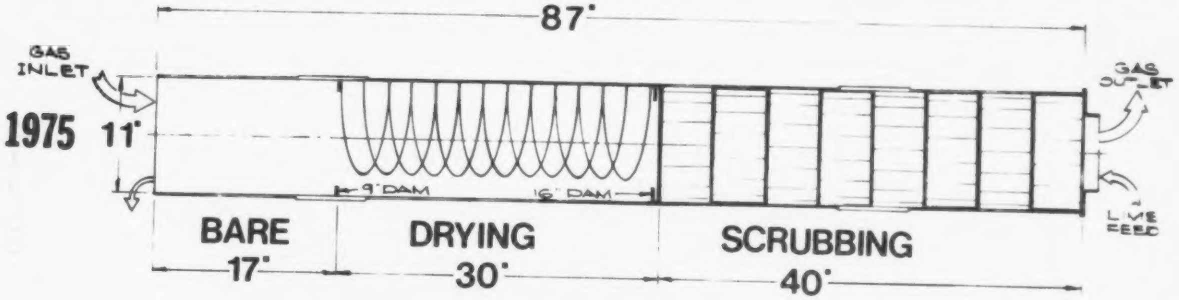


FIGURE 3
ORIGINAL SCRUBBER CONFIGURATION

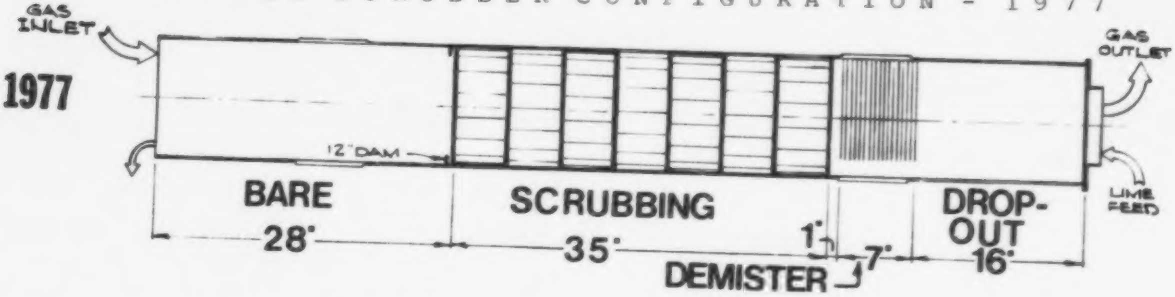


The gas exit section of the rotating kiln contained eight lifter box cages and 15 tons of chain. The center drying section had about five tons of chain in a "garland" arrangement. Except for a few test chains, all scrubber and scrubbed gas handling equipment was of mild steel.

From the start, tests on this first configuration indicated excellent SO_2 removal, but inadequate particulate capture. Particulate emissions were still twice the allowable limit.

We felt that, with our type of boilers and coal, we should be able to meet particulate as well as SO_2 requirements with this scrubber. Therefore, we shifted the scrubbing section to the center of the kiln, using heavier chains. (figure 4) We also eliminated the drier chains, added a de-mister section and a dropout, or disengaging section.

FIGURE 4
SECOND SCRUBBER CONFIGURATION - 1977



With this design, SO_2 collection further improved. The particulate collection was doubled - to about only 20% more than allowable. (see table 5)

TABLE 5
1977 SCRUBBER PERFORMANCE

	NATURAL	ALLOWED	ACHIEVED
SO_2	960	270	30
PART.	115	21	26

We now felt quite sure that, with only minor modifications, the scrubber would handle the load of all 3 boilers. This would be a substantial breakthrough since it eliminated the need for additional scrubbing devices for the other boilers. This offered significant savings in investment and operating costs.

Therefore, in early 1978, we tied in both small boilers to the scrubber, added a mist eliminator at the stack, enlarged the ID fan and added 30 tons more chain upstream of the scrubber section - back to the concept of drying. So we now have this configuration. (see figure 5 & 6)

FIGURE 5
FINAL CONFIGURATION

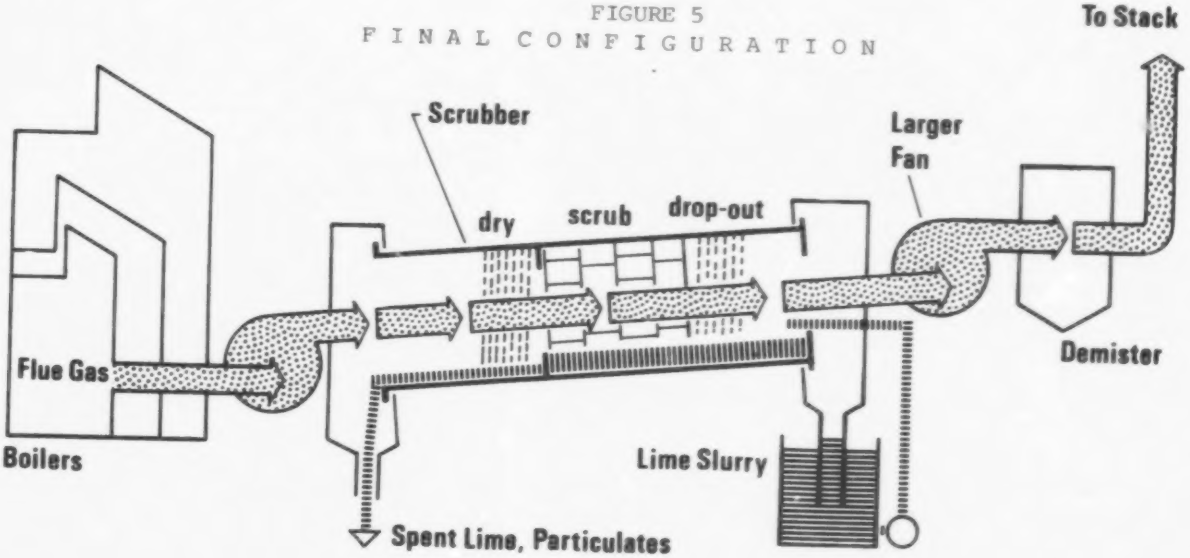
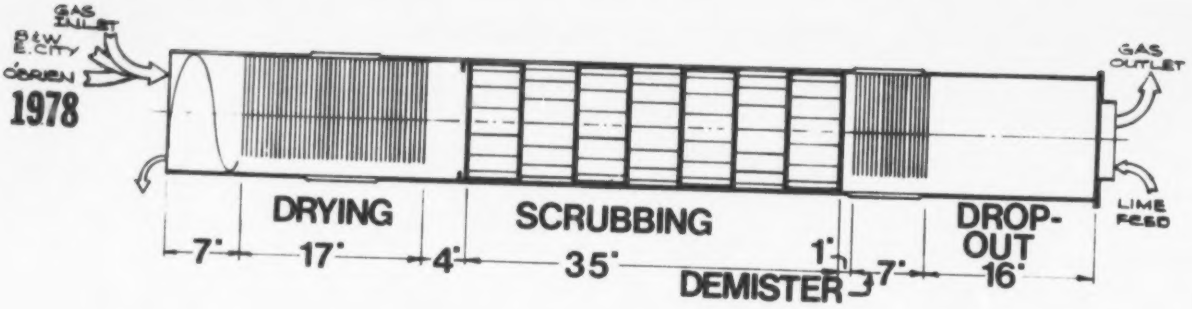


FIGURE 6

FINAL CONFIGURATION



In August of last year, we achieved the SO_2 and particulate limits on all 3 boilers and, shortly thereafter, obtained the final signed permit from the State of Illinois Enviromental Protection Agency. (see table 6)

TABLE 6

FINAL EMISSION TESTS

	UNABATED	ALLOWABLE	ACTUAL
SO_2	1408	396	42
PARTICULATE	145	49	37

Here are some operating characteristics of the scrubber.

The lime utilization is excellent (table 7). The water flow is low and we have operated with dry discharge. Our data and experience with dry discharge is limited, since our primary concern has been to meet emission limits and generate steam for pigment manufacturing. Also, recently an improved plant wide solid waste disposal system provides minimal economic incentive for adding the complexity of dry discharge.

TABLE 7

SCRUBBER FLOWS

LIME	1000 lbs/hr. (90 + % Utilization)
WATER IN	50 GPM
SLURRY OUT	30 GPM
pH	6.0

The energy use is quite low (table 8). Our total energy penalty is less than 3%. Many FGD's require from 3 to as much as 8% of the output.

TABLE 8
ENERGY USE

KILN	100 H.P.
I.D. FAN	400 H.P.
PUMPS	43 H.P.
TOTAL P	15" H_2O

Our actual costs are shown in table 9. Though we did invest $1,800,000 we modified the scrubber several times. We would anticipate that this system could be duplicated for less than $1,000,000. (in 1976 dollars)

TABLE 9
ANNUAL COSTS - BUDGETED FOR 1979

LIME PURCHASE	$170,000	
WASTE DISPOSAL	120,000	
POWER	50,000	
DEPRECIATION	150,000	($1,800,000 Investment)
MAINTENACE	200,000	
	$690,000	

A comparison of costs with other fuels shows that we can still use coal at lower cost than any other competitive fuel.

Since last fall we have had some other noteable successes. Monthly on stream time has never been below 90% and has averaged over 94%.

Recently we have experimented with lower cost raw materials and have been successful. We have found that lime kiln dust can be used as effectively as quicklime. Lime kiln dust is a by-product from Pfizer lime plants and all other lime plants. This has further reduced operating costs.

Also, actual maintenance for 1979 is well below what we had anticipated. These economic improvements have reduced our total operating cost to about 60¢/MM BTU - including depreciation!

Let me review what we have here - a stack gas scrubber that works. It is simple to operate, has demonstrated on-stream times in excess of 90% its first year, costs less than $0.60/MM BTU, and perhaps its most unique feature is, it was developed, designed and commissioned without public funds. This device was created entirely within the private sector! Classical economics wins again.

DESIGN GUIDELINES FOR AN OPTIMUM SCRUBBER SYSTEM

by

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ABSTRACT

The revised New Source Performance Standards (NSPS) for the utility industry mandates reduced particulate matter and sulfur dioxide emissions from new utility boilers. A wet scrubber system can be an advantage in controlling both of these emissions. Existing wet scrubber systems may meet the new standards with significant increase in power consumption. A careful design of the entire scrubber system, based on the experience gained at the existing installations, is necessary to ensure cost effectiveness.

The experience with existing wet scrubber systems used on coal-fired utility boilers is reviewed and their performance is correlated with power consumptions. Based on a correlation of scrubber pressure drop against outlet concentration, conventional scrubber systems would be able to meet the revised NSPS with a theoretical scrubber pressure drop of 17±2 in. W.G. Overall system pressure drop, however, could easily run as high as 30 in. W.G. Novel scrubber systems such as the electrostatically augmented scrubber may provide the necessary collection performance at lower pressure drops.

The performance of the various scrubber components such as mist eliminators and reheaters is reviewed. Operating problems are also discussed.

CONVERSION TABLE

To Convert From	To	Multiply By
Btu/lb	nm^3/hr (0°C)	2.324
scfm (60°F)	m^3/hr	1.61
cfm	m^3/hr	1.70
°F	°C	(°F-32)/1.8
ft	m	0.305
gal/mcf	$1/m^3$	0.134
gpm	1/min	3.79
gr/scf	gm/m^3	2.29
hp	kW	0.746
in.	cm	2.54
in. W.G.	mm Hg	1.87
lb	gm	454
psia	kilopascal	6.895
1 ton (short)	metric ton	0.907

DESIGN GUIDELINES FOR AN OPTIMUM SCRUBBER SYSTEM

INTRODUCTION

The U.S. Environmental Protection Agency has lowered its New Source Performance Standard for particulate emissions from coal-fired boilers to 0.03 lbs of particulate/million Btu.[1] In the case of power plants which require a scrubber system to meet SO_2 emission standards, it is economically advantageous to also collect the particulate matter with the scrubber system. But existing utility scrubber systems either would require relatively large power consumptions to meet the standard, or would be incapable of meeting it at all. Hence it is desirable to design an optimum wet scrubber system which would have a high and acceptable collection efficiency at low energy requirements.

The performance data and operating experiences of existing scrubber systems were summarized in an EPA report by Kashdan and Ranade (1979). This information is essential for the design of an optimum wet scrubber system for coal-fired utility boilers.

The particulate emissions from power plants exhibit tremendous variability in flyash particle size distribution, composition, and the flue gas composition. For given emission properties the scrubber components need to be chosen so that acceptable performance is obtained at the lowest cost. The past operating experience from the scrubber systems used with power plants will provide guidance in selecting various components of the scrubber system. However, the technology of the scrubber system components has not advanced far enough to prevent problems arising after construction. Flexibility of the design to allow easy replacements of various components is desirable to accomodate developments in the scrubber technology. Highlights of the review of operating experiences are presented in the next few pages.

PROCESS DESCRIPTION

For a complete understanding of the problem, the source of pollutant emissions must be considered as well as the collection device. A brief description of a coal-fired electric generating plant and its effluents follows with emphasis on aspects relevant to a scrubber system.

Modern coal-fired, electric generating plants consist of boilers, generators, condensers, coal handling equipment, dust collection and disposal equipment, water handling and treatment facilities, heat recovery systems (such as economizers and air heaters), and possibly flue gas desulfurization systems.

Boiler types in use include cyclone, pulverized, and stoker units, but nearly 90 percent are pulverized coal boilers (Sitig, 1977). Pulverized coal boilers are commonly classified as either wet bottom or dry bottom depending on whether the slag in the furnace is molten.

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[1] See Conversion Table, pg.2.

Two condensing cooling systems are used by the electric utility industry: the once-through system and the recirculatory system. In the once-through system, all the cooling water is discharged to a heat sink, such as a river or lake. In recirculating systems, cooling devices, such as cooling towers or spray ponds, permit the use of recirculated water.

Wet scrubbing systems in coal-fired electric generating plants may be used to collect particulate matter and/or to scrub SO_2 from the flue gas. In any case, a wet scrubbing system increases both the solid and wastewater disposal problems of the plant.

Combustion of coal in the furnace produces both flyash (airborne) and bottom ash (settled). Both bottom ash and collected flyash along with sludge from a throwaway flue gas desulfurization system (where used) are the major sources of solid waste from coal-fired utilities. These solid wastes, which are in a slurry form, are usually sluiced to a solid-liquid separator; the solids settle out and clarified water is returned to the system or discharged. Ultimate disposal of the wastes may be either in an onsite settling pond or, after further dewatering and treatment, in a landfill.

CHARACTERIZATION OF EMISSIONS FROM COAL-FIRED UTILITY BOILERS

The successful design of a wet scrubber system on a particular coal-fired boiler requires careful consideration of the flue gas characteristics of that boiler.

Physical and Chemical Properties of Flue Gas

In designing a wet scrubber system, the volume of gas handled, inlet and outlet temperatures, humidity, and SO_2 concentration are all important considerations. Typical power plant flue gas volumes range from 3000 to 4000 acfm/MW depending on coal composition, boiler heat rate, gas temperature, and amount of excess air. Because of economies of scale, the utility industry has tended toward larger and larger power stations implying that scrubber systems must be capable of handling volumes of gas as large as 4,000,000 acfm.

The temperature of the gas entering the scrubber is determined by the efficiency of the air heater. Most steam power plants operate in the range of 250-300°F downstream of the air heater. Exit temperatures from the scrubber vary with sulfur content and range from 150°F for coals with less than 1 percent sulfur to 180°F for coals containing above 3 percent sulfur (McIlvaine, 1974). Because exit temperatures are low, most scrubbing systems incorporate reheat systems which provide greater plume buoyancy and prevent corrosive condensation.

Flue gas contains from 5 to 15 percent moisture depending on the amount of volatile matter and on the moisture content of the coal. The concentration of sulfur dioxide in the flue gas depends on the sulfur content of the coal: for an average sulfur content of 2.5 percent, there will be approximately 1500 ppm of SO_2 in the flue gas (McIlvaine, 1974). On the average, 1-3 percent of the SO_2 will be converted to SO_3. Sulfur oxides in the flue gas make for a corrosive environment; special alloys, coatings, and linings must be used on scrubber internals.

Of particular concern to the designer of a wet scrubber system is the chlorine content of the coal. The chlorine content of coal (in the form of sodium and potassium chlorides) may vary from a trace amount to as high as 0.5 percent. During combustion, some of the chlorine is converted to hydrogen chloride or other volatile chlorides. Most of the hydrogen chloride will be absorbed in scrubbing liquor, thereby increasing the potential for chloride stress-corrosion.

Characterization of Flyash

The characteristics of flyash (concentration, size distribution, and chemical composition) affect both the performance and maintenance of the scrubber.

Particulate Emission Quantity

Particulate Emission Quantity--The concentration of flyash in utility flue gas depends primarily on the following variables: (1) amount of ash in the coal, (2) method of burning the coal, and (3) rate at which coal is burned (Sitig, 1977). Pulverized coal units produce greater quantities of dust than stoker or cyclone units. Furthermore, for a given furnace type, the flyash emission quantity will be approximately proportional to the ash content of the coal. Inlet dust loadings in utility flue gas may vary from 2 to 12 gr/dscf, but 4 or 5 gr/dscf is fairly typical.

In general, the size distribution of the flyash and not the emission quantity determines the collection efficiency of a particular scrubber. However, the dust concentration does affect the abrasiveness of the flue gas, and hence, the potential for eroding a scrubber system. In cases where the inlet dust loading is very heavy, some scrubbing systems use mechanical collectors before the scrubber.

Flyash Size Distribution--The particle collection efficiency of a scrubber is lowest for the fine particles (<3.0 microns, aerodynamic). Hence, the collection efficiency of a particular scrubber will depend on the amount of fine particles in the inlet dust.

Figure 1 shows flyash size distributions from four utility boilers. The fine fraction varies widely, ranging from roughly 4 percent to 45 percent of the inlet dust loading, and representing about 0.05 gr/dscf to 0.5 gr/dscf. This variation is accounted for in part by the coal and furnace type. Lignite, for example, appears to produce a very fine distribution. Because of the limited amount of data, however, generalizations are difficult to make. Further, the effect of process variables on the size distribution is not known. Suffice it to say that if the design of the optimum wet scrubber system is to be based on impactor measurements of the inlet flyash size distribution, then careful measurements in sufficient number must be made to accurately determine the fine particle fraction.

(Figure 1 shows that the flyash size distribution from the stoker unit had a large fraction of fine particles, contrary to what one would expect from this method of firing. The distribution was indeed biased toward the smaller sizes by the scrubbing system sampling duct which acted like a mechanical collector (Hesketh, 1975). Nevertheless, the sampled flue gas did contain approximately 0.1 gr/dscf below 3.0 microns.)

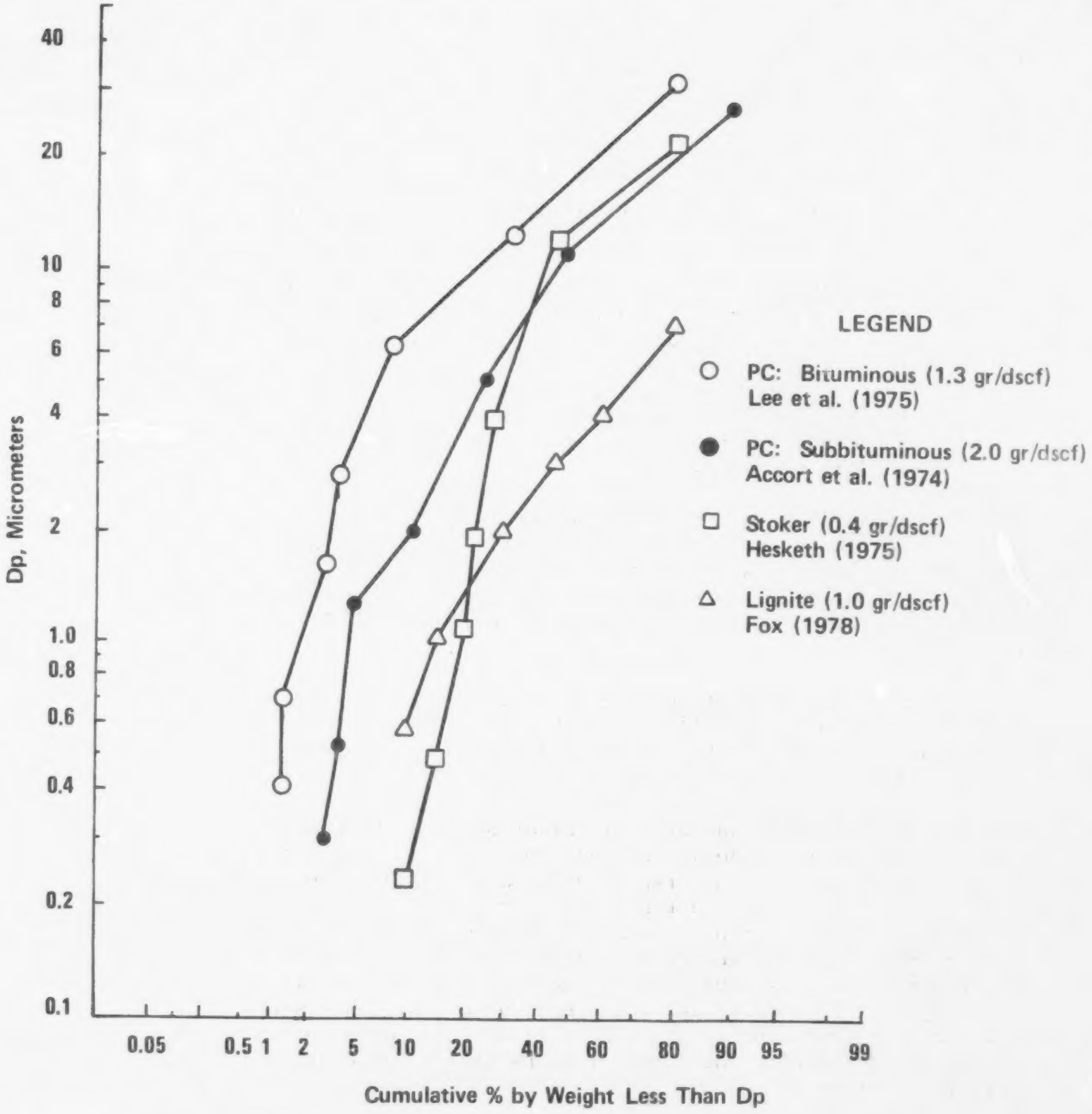

Figure 1. Flyash size distributions from four utility boilers.

Chemical Composition of Flyash--Flyash is composed primarily of silicates, oxides, sulfates, and unburned carbon. For purposes of designing a particulate scrubber system, the calcium oxide content of the flyash is an important consideration: the calcium oxide will scrub a certain amount of SO_2 thereby forming calcium sulfate and increasing scaling potential. In cases where the flyash was extremely alkaline, the design of a combined particulate-SO_2 scrubbing system encorporated the collected flyash as the scrubbing reagent (Grimm et al., 1978).

SUMMARY OF EXISTING SCRUBBER SYSTEMS IN THE U.S.

Table 1 is a summary of the design and operating parameters of the various particulate and particulate-SO_2 scrubber systems in use at coal-fired power plants across the U.S. Gas-atomized scrubbers, and particularly, venturis, are the most widely used scrubber design for particulate removal.

The newer installations generally have better particulate removal capabilities, greater availabilities (defined as the fraction of a year that the scrubber appeared to be in operable condition), and treat larger volumes of flue gas. Landfill and ponding are the predominant methods of waste disposal. Few of the existing scrubber systems are now meeting the New Source Performance Standard for particulates, 0.03 lb of particulate/million Btu, or about 0.017 gr/dscf. As shown in Table 1, the particulate scrubber at the Four Corners Station (Arizona Public Service) operates with an overall system pressure drop of 28 in. W.G. and is capable of just meeting the standard.

ESTIMATING POWER REQUIREMENTS

Estimating the power requirements of a particulate wet scrubber is a two-step process: first a determination of the size distribution of the dust is made; and second, an estimate is made of the power requirements for the scrubber which are necessary to meet emission standards. Two approaches, the contact-power rule and the cut-power rule, have been developed and are discussed below.

Contacting-Power Rule

The contacting-power rule, developed by Semrau (1977), represents a completely empirical approach to the design of particulate scrubbers. The fundamental assumption is that, for a given dust, scrubber performance depends only on the power consumed in gas-liquid contacting, regardless of scrubber size or geometry.

Power consumed in gas-liquid contacting depends on the manner in which the energy is introduced. For gas-atomized scrubbers, where the energy comes from the gas stream, theoretical power consumption is given by

$$P_G = 0.158\ \Delta P,\ \text{hp/1000 acfm} \qquad (1)$$

where ΔP = pressure loss across unit in inches W.G.

For preformed spray scrubbers, where the energy comes from the liquid stream, theoretical power consumption is given by

TABLE 1. CONDENSED SUMMARY OF PARTICULATE AND PARTICULATE-SO_2 SCRUBBERS IN THE U.S.

PARTICULATE-SO_2 SCRUBBERS

Utility	Pennsylvania Power Co	Kentucky Utilities	Montana Power Co	Tennessee Valley Authority	Tennessee Valley Authority	Arizona Public Service Co.	Northern States Power	Kansas City Power & Light	Kansas Power & Light	Nevada Power Co
Station	Bruce Mansfield No 1, 2	Green River Station	Colstrip No. 1, 2	Shawnee 10A	Shawnee 10B	Cholla Station	Sherburne No 1, 2	La Cygne No 1	Lawrence No 4	Reid Gardner No 1, 2, 3
Design and Operating Parameters				(Test facility)	(Test facility)					
Start up date	4/76	9/75	9/75	4/72	4/72	12/73	3/76	2/73	1/77	3/74
Reagent	lime	lime	flyash lime	lime limestone	lime limestone	limestone	limestone	limestone	limestone	soda ash
Vendor	Chemico	AAF	CEA	UOP	Chemico	R C	CE	B&W	CE	CEA
Design	Venturi	Venturi Moving Bed	Venturi Wash Tray	Moving Bed	Venturi Spray Tower	Venturi Spray Tower	Venturi Moving Bed	Venturi Sieve Tray	Rod Scrubber Spray Tower	Venturi Wash Tray
Number of equipped boilers	2	3	2	1	1	1	2	1	1	2
Number of scrubber modules	12	1	6	1	1	2	24	8	2	2
Installed scrubber capacity, MW	1650	180	720	10	10	115	1400	870	125	330
Collector preceding scrubber		Mech								Mech
Reheat?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bypass?	No	Yes	No	No	No	Yes	No	No	Yes	Yes
Annual cost, mills/kWh	4.25	2.0	0.26			2.2	0.4	1.4	NA	NA
Coal heating value, Btu/lb	11,900	10,800	8,840	10,500 (ave.)	10,500 (ave.)	10,400	8,300	9,000-9,700	10,000	11,800
Sulfur in coal, pct	4.7	3.7	0.8	coal type variable	coal type variable	0.5	0.8	5-6	0.5	0.6
Ash in coal, pct	12.5	13.4	9			13.5	9	20-30	9.8	9.4
Calcium oxide in ash, pct	NA	NA	22			3.5	NA	6.9	13.2	18
L/G, gal/1000 acf	20	39.5	15 for venturi 18 for spray	37	21 for venturi 9.4 for tower	10 for venturi 49 for tower	17 for venturi 10 for bed	12 for venturi 26.5 for tower	20 for scrubber 30 for tower	12.5
P particulate scrubber, in. W.G.	20	7	17	8-16	3-16	15	11	7	9	15
P system, in. W.G.	NA	NA	25.5			23.5	22	22	24	20
Inlet dust loading, gr/dscf	5-6.5	2.2	2.7	3.5-8.5	3.5-8.5	2.0	2.0-4.0	5.6	4.3	0.3-0.6
Inlet SO_2, ppm	2,200-2,600	2,200	800	2,500-4,000	2,500-4,000	420	400-800	4,500	425	300
Outlet dust loading, gr/dscf	0.007-0.017	99% (design)	0.018	0.035-0.090	0.003-0.050	0.016	0.035-0.044	0.074	0.04	0.02
SO_2 removal, pct	92% (design)	90	80	60-99	60-99	59	50-55	80	90	85
Waste disposal	Landfill	Pond	Pond	Pond	Pond	Pond	Pond	Pond	Pond	Pond
Availability	97+	85.4	90+			95	90	NA	NA	90
Reference	38, 10, 21	21, 22	21, 16, 27	31, 2, 39	31, 2, 39	21, 23, 20	10, 21, 19	10, 21, 24	10, 21, 15	20

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TABLE 1 (cont.) CONDENSED SUMMARY OF PARTICULATE AND PARTICULATE-SO_2 SCRUBBERS IN THE U.S.
PARTICULATE SCRUBBERS

Utility	Arizona Public Service	Pacific Power & Light	Public Service Company of Colorado			Minnesota Power & Light		Montana-Dakota Utilities
Station	Four Corners	Dave Johnston	Valmont	Cherokee	Arapahoe	Clay Boswell	Syl Laskin	Lewis and Clark
Design and Operating Parameters								
Start-up date	12/71	4/72	11/71	11/72-7/74	9/73	5/73	6/71	12/75
Vendor	Chemico	Chemico	UOP	UOP	UOP	Krebs	Krebs	R-C
Design	Venturi	Venturi	TCA	TCA	TCA	Preformed Spray	Preformed Spray	Venturi
Number of equipped boilers	3	1	1	3	1	1	2	1
Number of scrubber modules	6	3	2	9	1	1	2	1
Installed scrubber capacity, MW	575	330	118	660	112	350	116	55
Collector preceding scrubber			Mech	Mech/ESP	Mech/ESP			Mech
Reheat?	Yes	No	Yes	Yes	Yes	No	No	No
Bypass?	No	No	Yes	Yes	Yes	No	No	No
Annual cost, mills/kWh	NA	NA	NA	NA	NA	NA	NA	NA
Coal heating value, Btu/lb	9,200	7,430	10,800	10,100	10,100	8,400	8,400	6,450
Sulfur in coal, pct.	0.75	0.5	0.8	0.6	0.6	0.9	0.9	0.5
Ash in coal, pct.	22	12	9.0	12	12	9	9	8.5
Calcium oxide in ash, pct.	6.3	20	10	4	4	11	11	NA
L/G, gal/1,000 acf	8.5	13.3	50	50	50	8	8	11
ΔP particulate scrubber, in. W.G.	18	10	10 - 15	10 - 15	10 - 15	2.5	2.5	13
ΔP system, in. W.G.	28	15	NA	NA	NA	4	4	14.5
Inlet dust loading, gr/dscf	12	4	0.8	0.4 - 0.8	0.8	1.25	2	1
Inlet SO_2, ppm	650	500	500	500	500	1,125	1,125	520
Outlet dust loading, gr/dscf	0.01 - 0.02	0.04	0.02(min.)[a]	0.02(min.)[a]	0.02(min.)[a]	0.03	0.04 - 0.046	0.03
SO_2 removal, pct.	30 - 40	40	40	20	20	40	40	50
Waste disposal	Mine	Landfill	Landfill	Landfill	Landfill	Pond	Pond	Pond
Availability	100	NA	75	70 - 90	40 - 70	100	100	NA
Reference	38, 20	20	20, 29	20, 29	20, 29	20, 36	20, 36	20, 33, 32

[a] Best performance of scrubber at highest pressure drop (29).

$$P_L = 0.583\ \Delta P_L\ Q_L/Q_G,\ \text{hp/1000 acfm} \tag{2}$$

where ΔP_L = pressure loss in liquid, lb/in^2

Q_L = liquid flow rate, gal/min

Q_G = gas flow rate, ft^3/min

When scrubber overall particle collection efficiency for a constant inlet dust is measured over a range of power consumptions, it is often found that the "scrubber performance curve" plots as a straight line on log-log paper, implying a power relationship given by

$$N_T = \alpha P_T^{\ \gamma}$$

where N_T is the dimensionless number of transfer unit related to efficiency (η) by $N_T \equiv \ln (1/(1-\eta))$, and P_T is given by

$$P_T = P_G + P_L.$$

The empirical constants, α and γ, depend only on the characteristics of the particulate, but are little affected by scrubber size or geometry.

The contacting-power rule implies that scrubbers operated at higher power consumptions will be more efficient particulate collectors--provided the increased energy results in better gas-liquid contact. Figure 2, derived from the above Table 1, is a log-log plot of operating points, outlet dust loading at a given power consumption for various power plant scrubber systems. (Theoretical power consumption was determined by Equations 1 and 2. Plotting outlet dust loading against power consumption is essentially equivalent to the procedure used in the contacting-power rule, assuming that flyash size distributions are the same for various utility boilers.) As shown, the operating points can be readily fitted to a straight line, implying a power-function relationship between scrubber overall collection efficiency and power consumption. The least-squares correlation was $Y = 0.068X^{-1.41}$ and $r^2 = 0.86$. The good fit is quite remarkable given the variety of coals, furnaces, process variables, and inlet particle size distributions among the plants. Based on this correlation, to achieve the New Source Performance Standard for particulates of about 0.017 gr/dscf, approximately 2.7±0.3 hp/1000 acfm (95 percent confidence limits) theoretical power consumption, or equivalently, 17±2 in. W.G. pressure drop is required. Although this value is only approximate, it does underscore the fact that conventional scrubbers require a large power consumption to meet the New

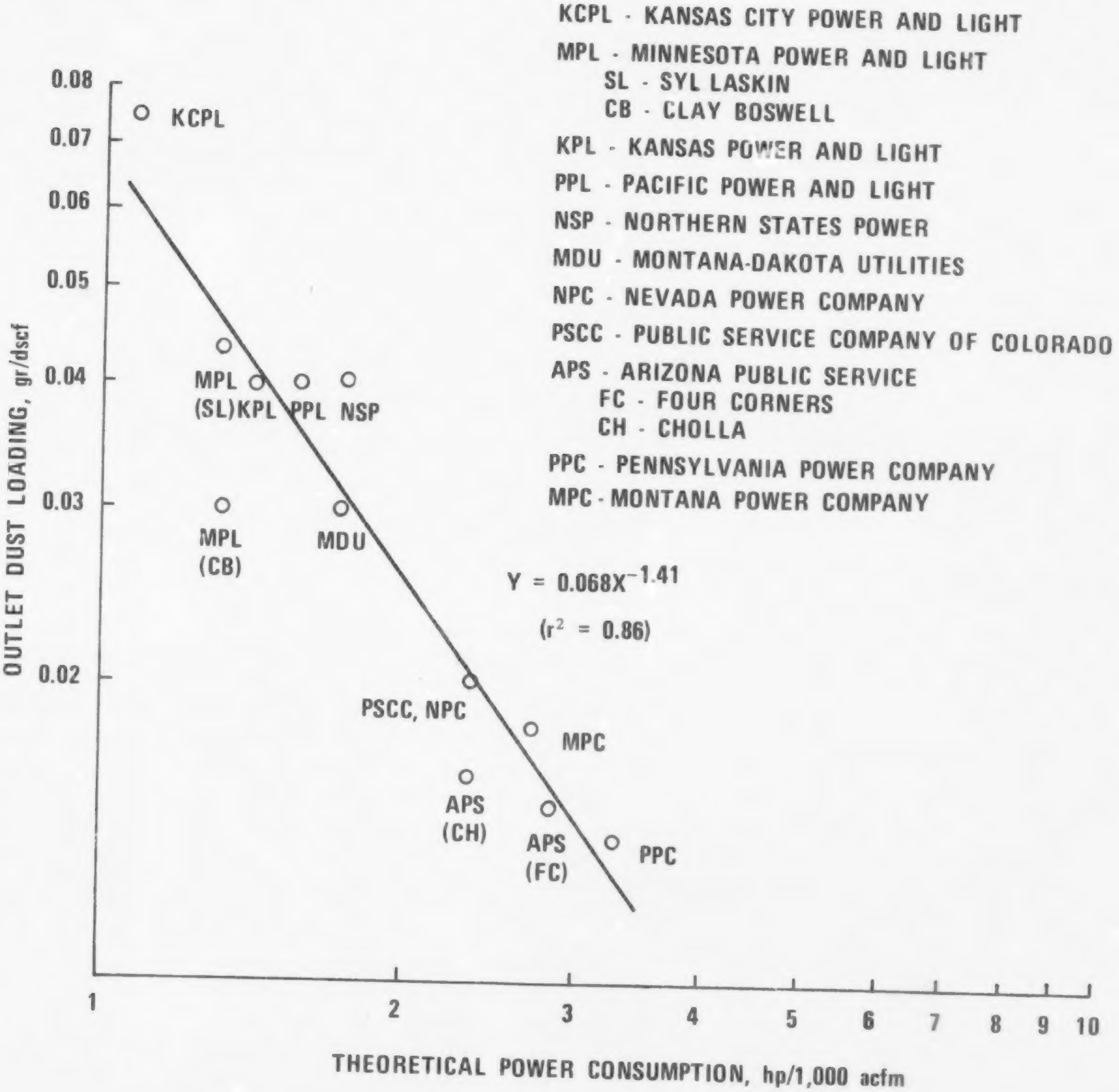

Figure 2. Correlation of scrubber outlet dust loading with theoretical power consumption.

Source Performance Standard. Further, this figure represents only the theoretical power consumption across the particulate scrubber. The actual system pressure drop will include fan losses, losses across the absorber, mist eliminator, and ductwork.

Cut-Power Rule

Whereas the contacting power rule provides an empirical approach to the design of particulate scrubbers, it lacks generality because it is specific to a particular dust. A more general and theoretical approach was taken by Calvert (1972, 1977) who related scrubber fractional efficiency to power consumption.

The cut-power rule uses the quantity called the "cut diameter," the diameter at which the collection efficiency of the scrubber is 50 percent. Most scrubbers that collect particles by inertial impaction perform in accordance with the following equation:

$$P = \exp(-A\, d_p^{\,B}) \qquad (3)$$

where P = particle penetration
A, B = constants
d_p = aerodynamic particle diameter

Assuming a log-normal distribution, Equation 3 can be integrated, yielding a plot of overall penetration against the ratio of required cut diameter to mass median diameter. Hence, by knowing the inlet particle size distribution and the efficiency needed to meet emission standards, one can determine the required cut diameter. For example, for a "typical" flyash particle size distribution of $d_g = 17$ μm, $\sigma_g = 4$, to achieve 99% collection efficiency would require a cut diameter of approximately 0.6 μm. To determine which scrubber types can meet this cut diameter, Calvert developed theoretical impaction models of scrubber performance (cut diameter) versus power consumption for various scrubber types. To achieve a cut diameter of 0.6 μm, a venturi scrubber would require a theoretical pressure drop of 15 in. W.G., which agrees with the figure of 17±2 in. W.G. determined from the empirical correlation above.

Figure 3 is a plot of theoretical venturi scrubber performance curves and actual performance points for scrubbers operating on coal-fired boilers (based on published data). The performance of the actual scrubbers suggests that, as expected, lower cut diameters (higher collection efficiencies) are achieved at the expense of greater power consumption. Further, the performance of the venturi scrubbers agrees well with the theoretically predicted performance for wettable particles. The venturi scrubber performance model is evaluated for different values of the dimensionless factor f. The value f = 0.50 corresponds to wettable particles, whereas f = 0.25 corresponds to nonwettable particles (Calvert, 1977).

The case of the moving-bed scrubber at Cherokee Station deserves special mention. As shown in Figure 3, independent measurements at similar pressure drops resulted in radically different values for the cut diameter. In this

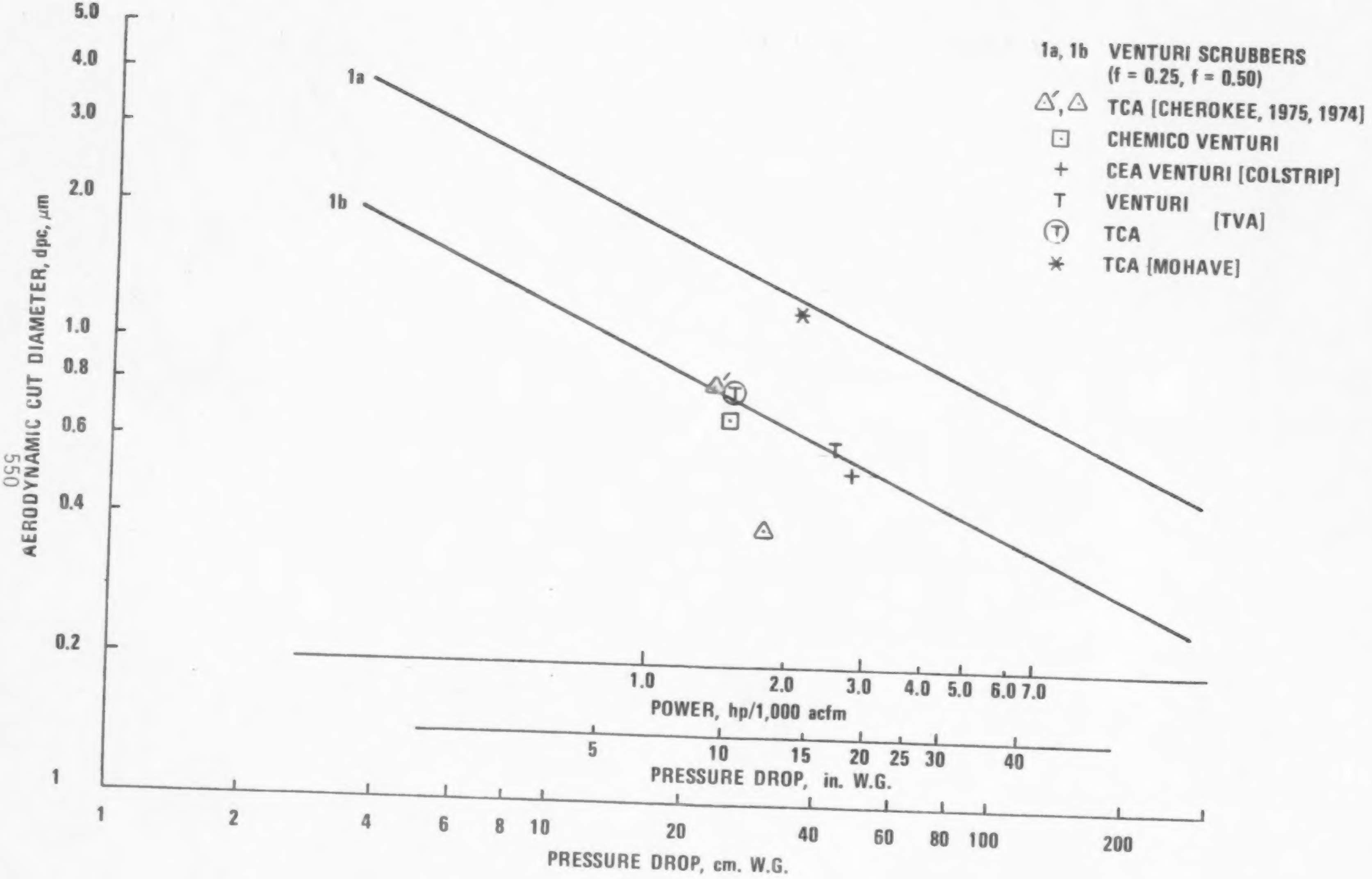

Figure 3. Theoretical and experimental cut diameters.

regard, Ensor et al., (1975) reported highly variable outlet particle concentrations which did not correlate with pressure drop suggesting the presence of reentrained solids from the mist eliminator. The authors concluded that the "evidence...weighs against one considering the agreement between predicted and experimental cut diameters to be anything more than coincidence."

In general, the limitations of the techniques for measuring flyash size distributions undermine the usefulness of the cut-power approach.

NOVEL SCRUBBERS

Conventional scrubbers collect particles primarily by inertial impaction. However, the collection efficiency of conventional scrubbers decreases significantly for fine particles, resulting in the need for relatively large power consumptions to remove the fine particles. As has been shown, flyash contains a substantial fraction of fine particles, with the result that scrubber systems operating on utility boilers may require overall system pressure drops as high as 30 in. W.G. This pressure drop represents a large power loss to a utility.

In 1973, EPA initiated a novel device evaluation program. The purpose of the program was to identify, evaluate, and where necessary, develop devices which would have better collection efficiencies for fine particles. The results of this program indicate that the most efficient novel scrubbers are those that utilize additional collection mechanisms other than just inertial impaction.

The most promising of these novel devices are electrostatically augmented scrubbers and condensation scrubbers. The former increases particle collection by increasing the electrostatic attraction between particles and droplets. The latter increases particle collection by growing particles into a size range which is easier to collect and, also, by increasing diffusiophoretic forces. Other novel scrubbers, which either consume large amounts of power or require the use of waste heat, are deemed inappropriate for use on utility boilers and are not discussed below.

Condensation Scrubbers--The use of condensing water to improve scrubber particle collection efficiency is not a new idea, but until EPA sponsored research on the subject, only small-scale laboratory studies had been done. Calvert (1973, 1974, 1975, 1977) developed models for particle collection in condensation scrubbers and attempted to verify those models in bench- and pilot-scale studies. His studies indicate that collection of fine particles in a condensation scrubber depends strongly on the inlet dust concentration and the flue gas enthalpy. In assessing the possible uses of condensation scrubbing, Calvert (1975) gives an approximate minimum enthalpy of 100 kcal/kg (about 180 Btu/lb) which would be necessary for high efficiency particle removal in a condensation scrubber. Flue gas from utility boilers typically contain 5 to 15 percent moisture. Even at 15 percent moisture, the enthalpy would only be about 180 Btu/lb, indicating that condensation scrubbers would have only marginal application to power plants. Furthermore, the collection efficiency of condensation scrubbers decreases with increasing dust concentration because there is less water available to condense on each particle. Theoretical calculations by Calvert (1974) have shown, for example, that for a three-plate condensation scrubber operating at a condensation ratio of 0.1 g vapor condensed/g dry air, particle collection efficiency for 0.75 μm (aerodynamic) particles decreased from 100 percent at a concentration of 2×10^5 particles/cm^3 (about 0.01 gr/scf, assuming a density of 2.0 gm/cm^3) to about 60 percent at a concentration of 10^7 particles/cm^3 (about 0.6 gr/scf). Insofar as utility flue gas may contain dust loadings as high as 8 gr/scf, condensation scrubbing does not seem very feasible.

In short, whereas it may be possible to incorporate some condensation effects in scrubbers operating on utility flue gas, a condensation scrubber per se would not be recommended.

Electrostatically Augmented Scrubbers--A number of novel devices have been developed recently which use electrostatic forces to enhance particle collection. The scrubber types using electrostatic augmentation vary considerably in design, but can be classified according to whether the particles and/or the water is charged, and whether an external electric field is applied.

Two of the most tested electrostatically augmented scrubbers are the TRW Charged Droplet Scrubber and the UW Electrostatic Scrubber. The TRW scrubber uses charged droplets and an externally applied electric field to collect particles. It has been used successfully on emissions from a coke oven battery. The UW scrubber charges both the water droplets and the particles (charged to opposite polarity); a pilot-scale unit has been successfully used on emissions from a power plant. Both of these devices have shown high efficiencies (over 90 percent) for submicron particles at substantially less power consumption than would be required for a conventional venturi.

Whereas the performance of these small-scale units has been encouraging, several points must be taken into consideration before a full-scale unit is planned for use on a power plant. First, utility flue gas contains a heavy dust loading, as large as 8 gr/dscf, and even greater. (The UW scrubber, although showing good collection efficiency of flyash from a power plant, because of the sampling arrangement, had extremely low inlet dust loadings of 0.5 gr/dscf or less (Pilat and Raemhild, 1978). Heavy dust loading, for example, would probably necessitate greater charging in a UW-type scrubber. Secondly, most utilities handle large volumes of gas compared to the volumes handled by these small units. The same cost savings may not be realized in a scaled-up version of these smaller units; the economics would have to be worked out on an individual basis.

MIST ELIMINATORS

Mist elimination is a requisite for every scrubber system. Mist eliminators remove scrubber-liquid droplets that are entrained in the flue gas and return the liquid to the scrubber. Poor mist elimination, an all too common problem, can have serious consequences, including corrosion downstream, an increase in particle outlet loading, an increase in power requirements for reheat, and an increase in water consumption.

In a system study for EPA, Calvert, Yung, and Leung (1975) evaluated the performance of various mist eliminators. The results of this study that are relevant to a utility scrubber system are as follows:

- Overall droplet collection efficiency of a mist eliminator depends on primary collection and reentrainment. Both overall and primary collection increase with increasing gas velocity. But at high gas velocities (nominally, 5 m/sec and over), reentrainment occurs, decreasing the overall collection even though primary collection remains high.
- Higher reentrainment velocities (greater mist eliminator capacity) are obtained with mist eliminators which have good drainage. Thus, horizonal gas flow mist eliminators have greater capacities than vertical gas flow types. Similarly, vertical gas flow mist eliminators with 45° baffles had larger capacities than those with baffles inclined at 30° or 0°.
- Pressure drop across a baffle mist eliminator is reasonably well predicted by a model based on the drag coefficient for a single plate held at an angle to the gas flow.
- Solids deposition is greater on inclined baffles than on vertical ones because of the increase in settling rate of suspended solids. Deposition rate decreases as the slurry flux on the surface increases.

A review of commercial mist eliminator designs in use in the utility industry revealed the following practices (Ellison, 1978):

- Vertical gas flow mist eliminators are used almost exclusively. The chevron multipass (continuous vane) construction and the baffle construction (noncontinuous slats) are common.
- Vane spacing is generally 1.5 to 30 inches except in the second stage of two-stage designs which generally use 7/8 to 1 inch spacing.
- Plastic is the most common material of construction due to reduced weight, cost, and corrosion potential.
- Precollection and prewashing stages are commonly used to improve demister operation.
- Demister wash systems typically operate intermittently using a mixture of clear scrubber liquid and fresh makeup water.

Horizontal gas flow mist eliminators have only recently been used in this country, although they are common in Japan and Germany. This type of mist eliminator has better drainage than vertical flow types, but space requirements are greater.

REHEATERS

General Considerations

Although reheating of scrubbed flue gas is not required by law, reheaters are often incorporated into flue gas wet scrubber systems. Usually, little attention is given to the design of reheaters, yet failure of the reheater can cause severe operational problems.

There are four major reasons for providing reheat in flue gas wet scrubber systems:

- avoid downstream condensation
- avoid a visible plume
- enhance plume rise and pollutant dispersion
- protection of the induced-draft fan.

Reheat may also prevent acid rain and stack icing as well as reduce plume opacity.

There are three types of reheaters commonly used at utilities. These are in-line reheaters, direct combustion reheaters, and indirect hot air reheaters. In-line reheaters are heat exchangers placed within the gas stream. Steam or water is used as the source of heat. Direct combustion reheaters burn either oil or gas, mixing the combustion gas with the flue gas. Combustion chambers can be located either in-line or external to the duct. Indirect hot air reheaters inject heated ambient air into the flue gas stream. The air is heated either in an external heat exchanger or in the boiler preheater. Alternatively, some utilities have chosen not to use any reheat system, operating the stack under wet conditions.

Experience gained with reheaters has produced some useful caveats. In-line reheaters are subject to plugging, corrosion, and vibration. Plugging can be minimized by good mist elimination and by soot blowing done at frequent intervals. Corrosion is a difficult problem since carbon steel, 304SS, 316SS, and Corten do not appear to be able to withstand combined acid and chloride-stress corrosion. More exotic and expensive materials, such as Inconel 625 and Hastealloy G, have been used successfully at Colstrip. Design against vibration can readily be done by using frequency analysis. Direct combustion reheaters are best designed with an external combustion chamber, preventing the problems encountered with in-line reheaters. Both direct combustion reheaters and indirect hot air reheaters require interlocks to prevent the heated gas from damaging ductwork when the cold flue gas is not present. At the Dave Johnston Plant, where reheat is not used, the induced draft fan is periodically washed with water to prevent solid deposits and an acid-resistant lining is used on the stack.

SCALING AND OTHER OPERATING PROBLEMS

Scaling is the single greatest operational problem in wet scrubbers and one that is most difficult to control. In scrubbers used for particulate removal only, the calcium and other alkalis present in the flyash react with SO_2 causing scale deposits (calcium sulfate). In lime and limestone systems, calcium sulfite (from the reaction of absorbed SO_2 and slurry alkali) and calcium sulfate (from the reaction of dissolved sulfite and oxygen) tend to precipitate out and form scale. In lime systems, calcium carbonate may also be precipitated when CO_2 from the flue gas reacts with the lime (pH is high).

Various techniques for controlling scale include:

- Control of pH -- If a limestone system is operated at pH's above 5.8 to 6.0 or if a lime system is operated above 8.0 to 9.0, there is a danger of sulfite scaling (Leivo, 1978). The pH is controlled by adjusting the feed stoichiometry. On-line pH sensors have been successful in controlling the feed in lime systems but not in limestone systems because the pH is fairly insensitive to the limestone feed rate in the normal pH range. However in the limestone system, the feed can be controlled by varying the flue gas flow rate. In particulate control systems, the pH is generally low, hold time in the retention tank is short, and suspended solids concentration is low. All these contribute to the formation of calcium sulfate scale. Hence, it is desirable to increase the scrubber liquor pH by addition of supplementary alkali.

- Hold Tank Residence Time -- By providing greater residence times in the scrubber hold tank, the supersaturation of the liquor can be decreased before recycle to the scrubber. Typical retention times of 5 to 15 minutes are used.

- Control of Suspended Solids Concentration -- Supersaturation can be minimized by maintaining a supply of seed crystals in the scrubber slurry. Typical concentrations range from 5 to 15 percent suspended solids. Solids are generally controlled by regulating slurry bleed rate.

- Regulating Oxygen Concentration -- Since calcium sulfate scaling depends on the presence of dissolved oxygen, control techniques center on regulating the oxygen concentration. In the forced oxidation method, air is bubbled into the reaction tanks to encourage sulfate crystal formation. These crystals have better settling characteristics than sulfite crystals. In the co-precipitation method, magnesium sulfite is used to depress the sulfate saturation level. Precipitation of sulfate in the holding tank is achieved by co-precipitation of sulfate with sulfite in a mixed crystal.

- Liquid-to-Gas Ratio -- High liquid-to-gas ratios reduce scaling potential since the scrubber outlet is more dilute with respect to absorbed SO_2. Unfortunately, increasing the liquid-to-gas ratio also increases operating costs and sludge disposal.

- Additives -- Two additives, Calnox 214DN and Calgon CL-14, when used together, have been found to effectively reduce sulfate scaling in limestone systems (Federal Power Commission, 1977).

- Alkali Utilization -- Experience at the TVA test facility at Shawnee indicated that certain mud-type solid deposits, which tended to form particularly in the mist eliminators, could be reduced by improving alkali utilization. Above about 85 percent alkali utilization, these solids could be removed easily with infrequent (once per 8 hours) washings. Control of calcium sulfate scaling at TVA was effected by varying the operating parameters listed above (Williams, 1977).

CONCLUSIONS AND RECOMMENDATIONS

Design of the optimum wet scrubber system for use on coal-fired utility boilers is a two-step process consisting of characterizing the inlet gas stream, and then choosing the best designs for the various scrubber components based on operating experiences and research studies.

Characterization of the inlet flue gas stream is essential, but too frequently, neglected. The following properties should be determined.

Flyash Size Distribution -- Flyash size distributions vary greatly among power plants, depending on boiler and coal types. For a particular scrubber, particle collection efficiency is determined by the inlet size distribution.

Flyash Composition -- The chemical composition of the flyash is important. If the flyash contains substantial quantities of alkalis, calcium and magnesium oxides, it will scrub some SO_2 from the flue gas leading to scale formation. Flyash may also contain chlorides which can cause stress corrosion in stainless steels.

Flue Gas Composition -- The concentration of SO_3 (or H_2SO_4) should be determined because of its corrosiveness. Flue gas may also contain hydrogen chloride which poses another corrosion problem.

Once the inlet gas stream has been characterized, it is necessary to select the best scrubber components to obtain maximum performance. The choice of components should be based on past operating experiences and research studies. Unfortunately, operating experiences do not always present a consistent picture, making it difficult to formulate hard-and-fast rules. It should also be borne in mind that scrubber design technology has not advanced far enough to prevent problems from arising after construction. Hence the best overall designs are those that are flexible enough to permit easy replacement of damaged parts.

This study recommends the following for the various scrubber components.

Particulate Scrubber and SO_2 Absorber -- Current practice suggests the use of simpler designs for both the particulate scrubber and SO_2 absorber. Hence, of the conventional particulate scrubber types, a gas-atomized scrubber, such as a venturi or rod scrubber, is recommended. Other types are less efficient or have more operating problems. Also, spray towers are preferable for use as the SO_2 absorber.

Based on a correlation of scrubber performance against energy requirements, a theoretical pressure drop of 17±2 in. W.G. would be necessary to meet the New Source Performance Standard of 0.03 lbs particulate/million Btu in a conventional scrubber. When fan losses and pressure drops across the absorber, ductwork, and mist eliminator are taken into account, total system pressure drop may run as high as 30 in. W.G. If this energy requirement is considered too high, a novel particulate scrubber should be chosen. Of the novel scrubbers tested by EPA to date, the electrostatically augmented scrubbers appear to be the most suitable for use on coal-fired utility boilers. Pilot units have shown good collection efficiency for flyash, coke oven battery emissions, and steel mill electric arc furnace emissions.

Mist Eliminator -- Horizontal mist eliminators have greater capacities than vertical types, but space requirements are also greater. Vertical mist eliminators are best designed with sharp angled baffles to promote good drainage.

Reheaters -- Operating experience with reheaters militates against the use of in-line reheaters because of combined acid and chloride stress corrosion. The two other types of commonly used reheaters, direct combustion and indirect hot air reheaters, are recommended and should be designed with interlocks to prevent heated gas from damaging ductwork when flue gas is not present. Adequate mixing is sometimes a problem with these types of reheaters.

Materials of Construction -- The most common construction material for scrubbers is 316 stainless steel. At points of high abrasion, wear plates, brick linings, or high grade nickel alloys are recommended. The higher grade alloys are also recommended in areas subject to chloride attack.

The best material for in-line reheaters appears to be the higher grade alloys--Inconel and Hastelloy have worked well at Colstrip (Montanta Power). Carbon steel and lower grade stainless steels have worked at some plants but have failed at others.

Plastic is the best material for mist eliminators because of low cost, light weight, and reduced corrosion potential.

Waste Disposal -- Disposal of collected flyash from a particulate scrubber is easily controlled, typically it is disposed of along with bottom ash. With a dual-function particulate-SO_2 scrubber system, waste disposal is problematic because of the thixotropic nature of the sludge. Ponding is the most common and least expensive method of disposal, but creates a large unreclaimable area. Landfill is a better method of disposal, but the sludge requires greater dewatering as well as stabilization. In some site-specific cases, it may be possible to use less common places, such as a dry lake (arid regions) or a mine.

REFERENCES

1. Accortt, J.L., A.L. Plumley, and J.R. Martin. "Fine Particulate Matter Removal and SO_2 Absorption with a Two-State Wet Scrubber," EPA-APT Fine Particle Scrubber Symposium, San Diego, May 1974.

2. Bechtel Progress Report, "EPA Alkali Scrubbing Test Facility TVA Shawnee Power Plant," June 1977.

3. Calvert, S., J. Goldshmid, D. Leith, and D. Methta. Scrubber Handbook, NTIS No. PB 213-016, July 1972.

4. Calvert, S., J. Goldshmid, D. Leith, and N. Jhaveri. Feasibility of Flux Force/Condensation Scrubbing for Fine Particulate Collection, EPA-650/2-73-036, NTIS No. PB 227-307, October 1973.

5. Calvert, S., and N. Jhaveri. "Flux-Force Condensation Scrubbing," in EPA Fine Particle Scrubber Symposium, EPA-650/2-74-112, NTIS No. PB 239-335, October 1974.

6. Calvert, S., N. Jhaveri, and T. Huisking. Study of Flux Force Condensation Scrubbing of Fine Particles, EPA-600/2-75-018, NTIS No. PB 249-297, August 1975.

7. Calvert, S., S. Yung, and J. Leung. Entrainment Separators for Scrubbers-Final Report, NTIS No. PB 248-050, August 1975.

8. Calvert, S. "How to Choose a Particulate Scrubber," Chemical Engineering, Vol. 18, No. 84, August 29, 1977, pp.54-68.

9. Calvert, S., and S. Gandhi. Fine Particle Collection by a Flux-Force Condensation Scrubber: Pilot Demonstration, EPA-600/2-77-238, NTIS No. PB 277-075, December 1977.

10. Devitt, T., R. Gerstle, L. Gibbs, S. Hartman, and N. Klier. Flue Gas Desulfurization System Capabilities for Coal-Fired Steam Generators. Volume II Technical Report, EPA-600/7-78-032b, NTIS No. PB 279-417, March 1978.

11. Ellison, W. "Scrubber Demister Technology for Control of Solids Emissions from SO_2 Absorbers," in Symposium on the Transfer and Utilization of Particulate Control Technology, EPA-600/7-79-044c, February 1979.

12. Ensor, D. et al. Evaluation of a Particulate Scrubber on a Coal-Fired Utility Boiler, NTIS No. PB 249-562, November 1975.

13. Federal Power Commission. The Status of Flue Gas Desulfurization Applications in the United States: A Technological Assessment, July 1977.

14. Fox, Harvey. Personal communication, Research-Cottrell, Bound Brook, New Jersey, July 1978.

15. Green, K., and J. Martin. "Conversion of the Lawrence No. 4 Flue Gas Desulfurization System," in Proceedings: Symposium on Flue Gas Desulfurization - Hollywood, Florida, NTIS No. PB 282-091, November 1977.

16. Grimm, C., J.Z. Abrams, W.W. Leffman, I.A. Raben, and C. LaMantia. "The Colstrip Flue Gas Cleaning System," Chemical Engineering Progress, Vol. 74, No. 2, February 1978, pp.51-57.

17. Hesketh, H.E. "Pilot Plant SO_2 and Particulate Removal Study, Report of Fiscal Year 1974-1975 Operations," Sponsored by Illinois Institute for Environmental Quality and Southern Illinois University, Project No. 10.027, August 1975.

18. Kashdan, E.R. and M.B. Ranade. Design Guidelines for an Optimum Scrubber System, EPA-600/7-79-018, NTIS No. PB 292-327, January 1979.

19. Kruger, R., and M. Dinville. "Northern States Power Company Sherburne County Generating Plant Limestone Scrubber Experience," Presented at the Utilities Representative Conference on Wet Scrubbing, Las Vegas, Nevada, February 1977.

20. LaMantia, C. et al. Application of Scrubbing Systems to Low Sulfur/Alkaline Ash Coals, EPRI FP-595, December 1977.

21. Laseke, B. EPA Utility Flue Gas Desulfurization Survey: December 1977-January 1978, EPA-600/7-78-051a, NTIS No. PB 279-011, March 1978.

22. Laseke, B. Survey of Flue Gas Desulfurization Systems: Green River Station, Kentucky Utilities, EPA-600/7-78-048e, NTIS No. PB 279-543, March 1978.

23. Laseke, B. Survey of Flue Gas Desulfurization Systems: Cholla Station; Arizona Public Service Company, EPA-600/7-78-048a, NTIS No. PB 281-104, March 1978.

24. Laseke, B. Survey of Flue Gas Desulfurization Systems: LaCygne Station, Kansas City Power and Light Company, EPA-600/7-78-048d, NTIS No. PB 281-107, March 1978.

25. Lee, R.E., H.L. Crist, A.E. Riley, and K.E. MacLeod. "Concentration and Size of Trace Metal Emissions from a Power Plant, a Steel Plant, and a Cotton Gin," Environmental Science & Technology, Vol. 9, No. 7, July 1975, pp.643-647.

26. Leivo, C.C. Flue Gas Desulfurization Systems: Design and Operation Considerations, Volume II, Technical Report, EPA-600/7-78-030b, NTIS No. PB 280-254, March 1978.

27. McCain, J.D. CEA Variable-Throat Venturi Scrubber Evaluation, EPA-600/7-78-094, NTIS No. PB 285-723, June 1978.

28. McIllvaine, R.W. The McIllvaine Scrubber Manual, Volume II, The McIllvaine Company, 1974.

29. Pearson, B., Private communication, Public Service Company of Colorado.

30. Pilat, M., and G. Raemhild. "University of Washington Electrostatic Scrubber Evaluation at Coal-Fired Power Plant," EPA-600/7-78-177b, NTIS No. PB 292-646, December 1978.

31. Rhudy, R., and H. Head. "Results of EPA Flue Gas Characterization Testing at the EPA Alkali Wet-Scrubbing Test Facility," Presented at the 2nd EPA Fine Particles Scrubber Symposium, EPA-600/2-77-193, NTIS No. PB 273-828, September 1977.

32. Richmond, M. and H. Fox, Private communication, Research-Cottrell, Inc.

33. Sadowsky, D., Private communication, Montana-Dakota Utilities.

34. Semarau, K. "Practical Process Design of Particulate Scrubbers," Chemical Engineering, Vol. 84, No. 20, September 26, 1977.

35. Sitig, M. Particulates and Fine Dust Removal, Processess and Equipment, Noyes Data Corporation, Park Ridge, New Jersey, 1977.

36. VanTassel, D., Private communication, Minnesota Power and Light.

37. Williams, J.E. "Mist Eliminator Testing at the Shawnee Prototype Lime/Limestone Test FAcility," 2nd US/USSR Symposium on Particulate Control, EPA-600/7-78-037, NTIS No. PB 279-628, March 1978.

38. Winkler, P., Private communication, Chemico Air Pollution Control Company.

39. Dallabetta, G., Private communication, Bechtel Corporation.

TESTS ON UW ELECTROSTATIC SCRUBBER FOR PARTICULATE AND SULFUR DIOXIDE COLLECTION

by

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Abstract

The University of Washington Electrostatic Scrubber pilot plant was tested for particulate and sulfur dioxide collection at the unit no. 2 coal-fired boiler at the Centralia Power Plant. The UW Electrostatic Scrubber involves the use of electrostatically charged water (or alkaline absorbing liquor) to collect air pollutant particles charged to the polarity opposite from the droplets and to absorb gaseous air pollutants. The portable UW Electrostatic Scrubber pilot plant (located inside a 40 ft. trailer) is designed for 1,000 acfm gas flow at the inlet to the scrubber: however, at Centralia inlet flows as high as 1,600 acfm were used. Simultaneous inlet-outlet source tests using the UW Source Test Cascade Impactors (Mark 10 model at the inlet to the scrubber and Mark 20 model at the outlet) and in-stack filters showed the overall particle collection efficiency ranged from 99.30 to 99.99% (depending on the scrubber operating conditions) and the outlet particle concentration ranging from .00018 to .0116 grains/sdcf. Using a sodium carbonate scrubbing liquor, the sulfur dioxide collection efficiency ranged from 36.2 to 98.8% depending on the operating parameters such as the liquor to gas flow rate ratio, liquor pH, inlet SO_2 concentration, etc., and spray voltage. The test results illustrate that the addition of electrostatic charging of the aerosol particles and the spray liquor droplets can enhance the collection efficiency for both particulates and sulfur dioxide.

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Tests on UW Electrostatic Scrubber for Particulate and Sulfur Dioxide Collection

by

Michael J. Pilat

I. INTRODUCTION

A. Objectives of Research Project

The objectives of this on-going research project are to demonstrate the effectiveness of the UW Electrostatic Scrubber for controlling emissions of fine particulates and gaseous air pollutants from various industrial sources. The test data obtained is to be used to improve scrubber performance and to develop preliminary designs and economic information of full-scale electrostatic scrubber systems.

B. Review of Previous Work

Penney (1944) patented an electrified liquid spray test precipitator involving particle charging by corona discharge and droplet charging by either ion impaction or induction. Penney's system consisted of a spray scrubber with electrostatically charged water droplets collecting aerosol particles charged to the opposite polarity. Kraemer and Johnstone (1955) reported theoretically calculated single droplet (50 micron diameter droplet charged negatively to 5,000 volts) collection efficiencies of 332,000% for 0.05 micron diameter particles (4 electron unit positive charges per particle). Pilat, Jaasund, and Sparks (1974) reported on theoretical calculation results and laboratory tests with an electrostatic spray scrubber apparatus. Pilat (1975) reported on field testing during 1973-1974 with a 1,000 acfm UW Electrostatic Scrubber (Mark 1P model) funded by the Northwest Pulp and Paper Association. Pilat and Meyer (1976) reported on the design and testing of a newer 1,000 acfm UW Electrostatic Scrubber (Mark 2P model) portable pilot plant funded by the EPA. Pilat, Raemhild, and Harmon (1977) reported on tests of the UW Electrostatic Scrubber pilot plant (Mark 2P model) on collecting laboratory generated DOP aerosols and emissions from a coal-fired boiler and an electric arc steel furnace. Pilat, Raemhild, and Gault (1978) reported on some of the results of SO_2 and particulate collection efficiency tests performed on the UW Electrostatic Scrubber at the Centralia Coal-Fired Power Plant. Pilat, Raemhild, and Prem (1978) reported on the tests at a steel plant (Bethlehem Steel Co., Seattle). The UW Electrostatic Scrubber (patent pending) has been licensed to the Pollution Control Systems Corporation (of Renton and Seattle, Washington) for production and sales.

II. Description of UW Electrostatic Spray Scrubber

The UW Electrostatic Scrubber involves the use of electrostatically charged water droplets to collect air pollutant particles electrostatically charged to a polarity opposite from the droplets. A schematic illustration of the UW Electrostatic Scrubber system is presented in Figure 1.

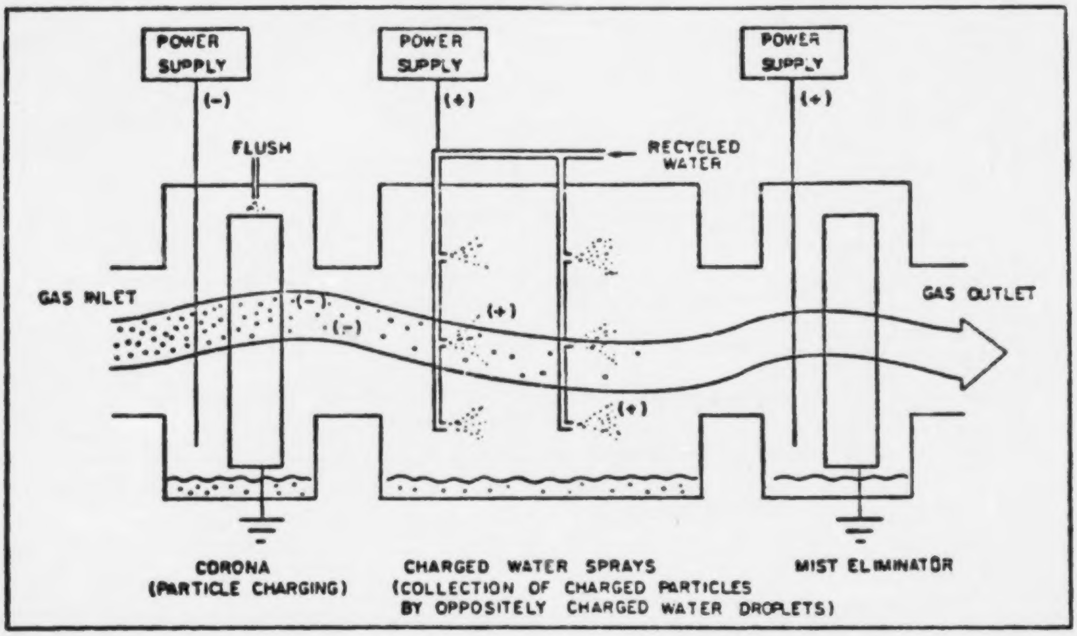

POWER SUPPLY
(-)
POWER SUPPLY
(+)
POWER SUPPLY
(+)
FLUSH
RECYCLED WATER
GAS INLET
(-)
(-)
(+)
(+)
GAS OUTLET
CORONA (PARTICLE CHARGING)
CHARGED WATER SPRAYS (COLLECTION OF CHARGED PARTICLES BY OPPOSITELY CHARGED WATER DROPLETS)
MIST ELIMINATOR

Figure 1. UW Electrostatic Scrubber

The particles are electrostatically charged (negative polarity) in the corona section. From the corona section the gases and charged particles flow into a scrubber chamber into which electrostatically charged water droplets (positive polarity) are sprayed. The gases and some entrained water droplets flow out of the spray chamber into a mist eliminator consisting of a positively charged corona section in which the positively charged water droplets are removed from the gaseous stream.

The general layout of the UW Electrostatic Scrubber pilot plant (Mark 2P model) which was used during the tests at the Centralia Power Plant is shown in Figure 2. The system (in the direction of gas flow) includes a gas cooling tower, an inlet test duct with sampling port, a particle charging corona section (corona #1, not used for these tests), a charged water spray tower (tower #1, not used for these tests), a a particle charging corona section (corona #2), a charged water spray tower (tower #2), a positively charged corona section to collect the positively charged water droplets, an outlet test duct with sampling port, and a fan.

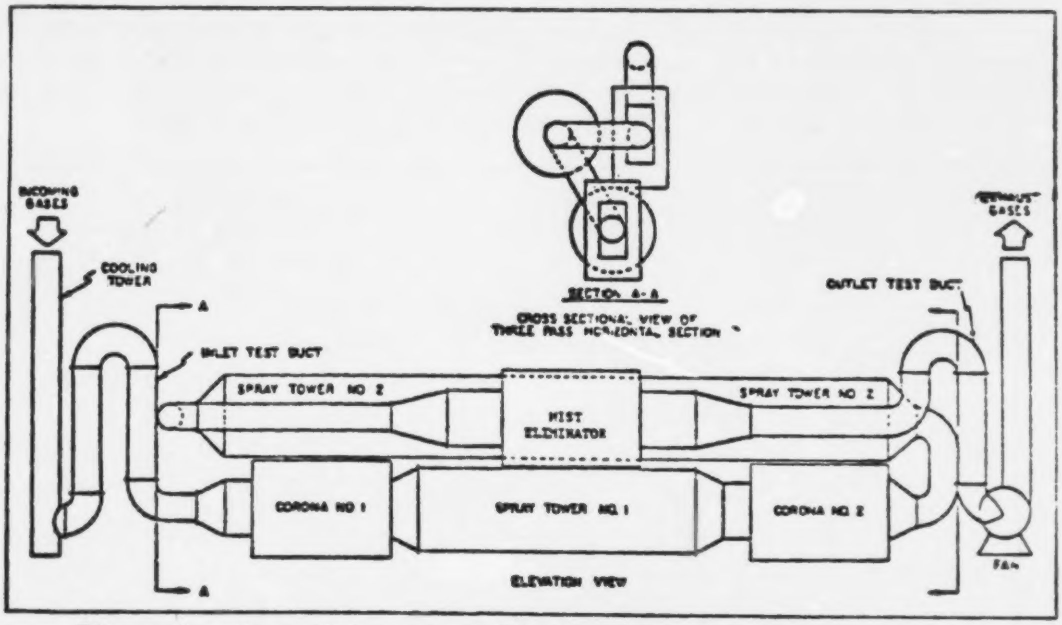


Figure 2. General Layout of Electrostatic Scrubber Pilot Plant (Model Mark 2P)

The model Mark 2P has a scrubbing liquor recycle system. This system utilizes an electrically isolated pump, insulated hosing, and a current limiting spray system for current containment and safety.

III. Experimental Procedure

The particle size distributions were measured simultaneously at the inlet and outlet of the elctrostatic scrubber using UW Source Test Cascade Impactors. The inlet test port is located downstream of a spray cooling tower (as shown in Figure 2) and hence, the measured particle collection efficiencies are for the electrostatic scrubber portion of the system. The 27 stage Mark 10 model (sampling at about 0.2 acfm) was used at the inlet where the particle concentration is higher. The 14 stage Mark 20 model (sampling at about 2.0 acfm) was used at the scrubber outlet where the particle concentration is typically low. Both the Mark 10 and Mark 20 models utilize reduced absolute gas pressure in the outlet jet stages in order to provide stage aerodynamic cut diameters (d_{50}) down to about 0.02 microns.

Thermo Electron Model 40 Fluorescent SO_2 Analyzer was used to measure SO_2 levels in the gas stream at the inlet and outlet of the pilot plant. The principle of operation of this monitor is based upon the measurement of the fluorescence of SO_2 produced by its absorption of ultraviolet radiation. The analyzer was connected to a strip chart recorder so that 5-minute averages of the inlet and outlet SO_2 concentrations were used to calculate the scrubber's SO_2 collection efficiencies.

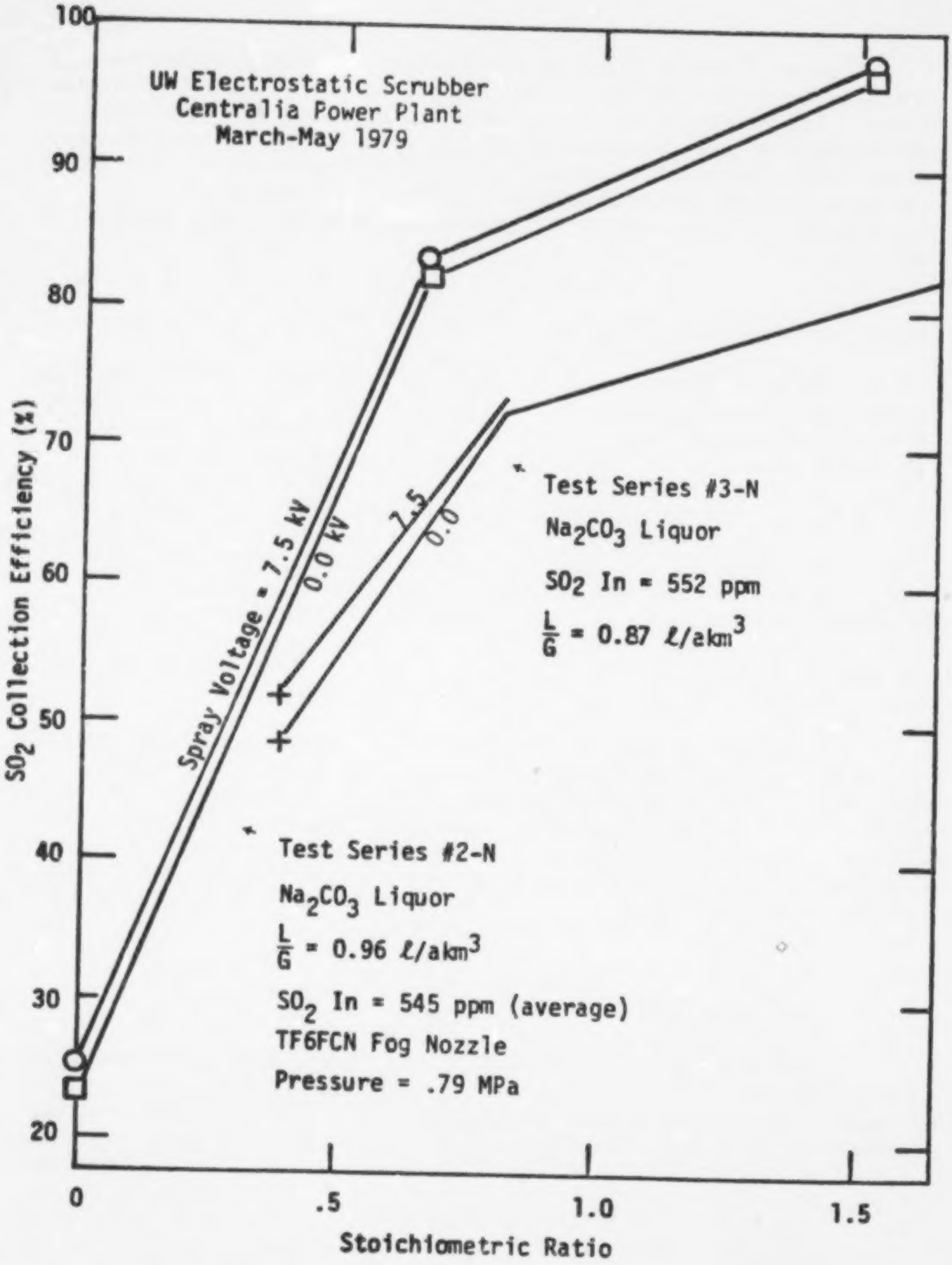
IV. Results of Particulate Tests

In October 1977, the UW Electrostatic Scrubber pilot plant (Mark 2P model) was transported to the Centralia Steam-Electric Project (two 655-megawatt pulverized coal-fired boilers) operated by Pacific Power and Light Company. A sample gas stream was tapped from the outlet of PP & L no. 2 and transported via ducting to the Electrostatic Scrubber pilot plant. The UW Electrostatic Scrubber pilot plant system was modified prior to testing by: (1) the installation of a larger booster fan at the inlet to the scrubber in order to accomodate the large negative pressure (around -14 inches water) in the main duct and to allow a higher gas flow rate through the scrubber pilot plant; and (2) the connection of a newly constructed liquor recycle system in a 40 ft. trailer to the spray scrubber tower which enabled operation with either an open-loop or a closed-loop liquor recycle system.

The results of the particle collection efficiency tests over the 0.075 to 15 micron aerodynamic diameter size range are presented in Figure 3. These efficiency curves are based on log-normal approximations of the inlet and outlet particle size distributions, and hence the minimum in the collection efficiency at about 0.5 microns diameter is smoothed out. The tests were run in an open-loop liquor recycle mode with the water used as the scrubbing liquor. The outlet particle mass concentration for these tests ranged from .00065 to .00459 grains/sdcf.

V. Results of Sulfur Dioxide Tests

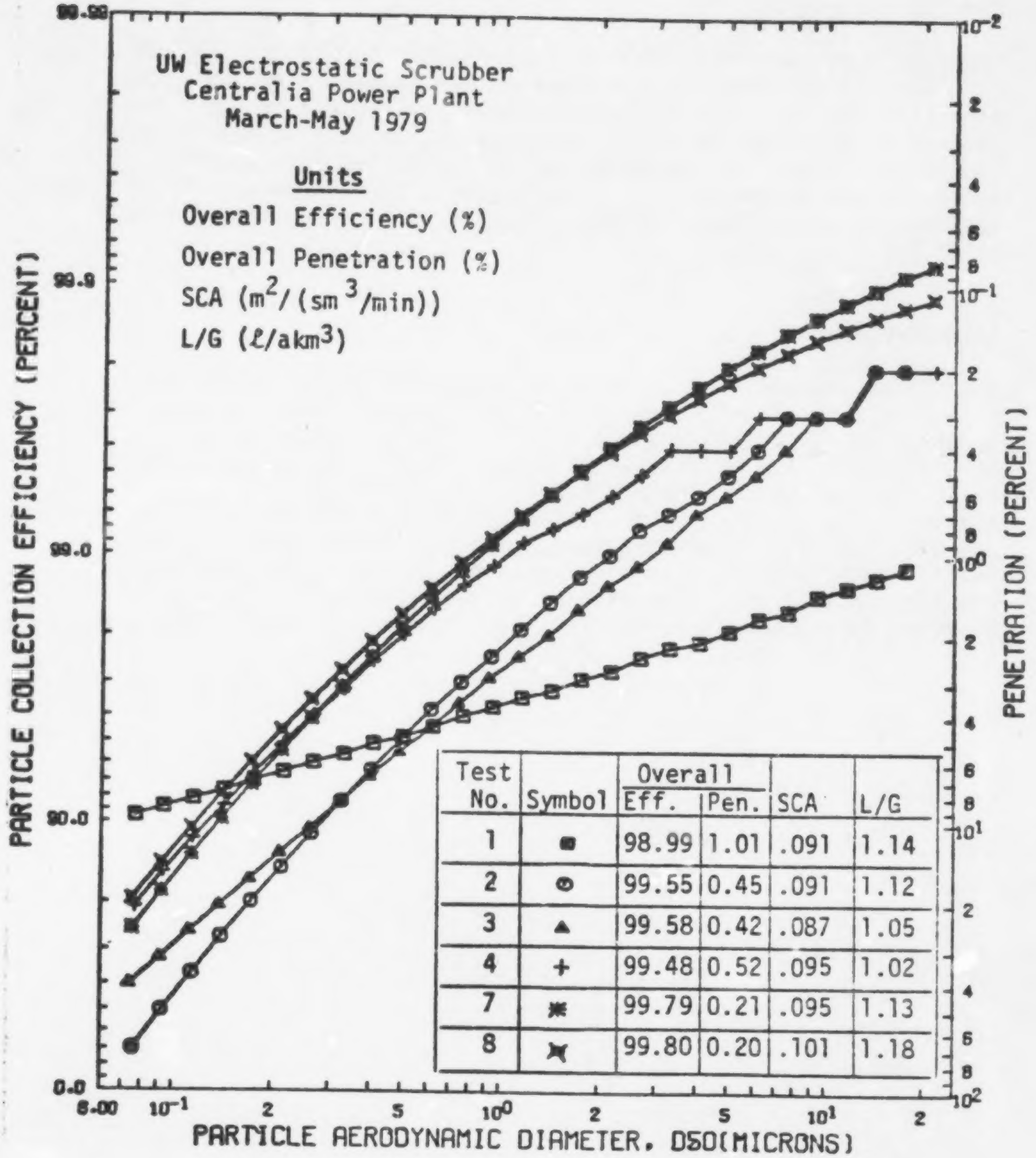
Sulfur dioxide collection efficiency tests were conducted at the Centralia Power Plant with an open-loop liquor system using scrubber liquor of water and of sodium carbonate solution. The measured SO_2 collection efficiencies were found to be a function of the liquor/gas flow rate ratio (L/G), the SO_2 inlet concentration, the stoichrometric ratio (moles of alkaline liquor sprayed/moles of inlet SO_2), and the liquor spray voltage. Figure 4 shows that the SO_2 collection efficiency increases with incoming stoichrometric ratio, with increasing spray voltage, and with increasing liquor/gas flow rate ratios.



* Test Series #3-N
Na_2CO_3 Liquor
SO_2 In = 552 ppm
$\frac{L}{G}$ = 0.87 ℓ/akm^3

* Test Series #2-N
Na_2CO_3 Liquor
$\frac{L}{G}$ = 0.96 ℓ/akm^3
SO_2 In = 545 ppm (average)
TF6FCN Fog Nozzle
Pressure = .79 MPa

Figure 4. SO_2 Collection Efficiency as a Function of Stoichrometric Ratio



Test No.	Symbol	Overall Eff.	Overall Pen.	SCA	L/G
1	■	98.99	1.01	.091	1.14
2	⊙	99.55	0.45	.091	1.12
3	▲	99.58	0.42	.087	1.05
4	+	99.48	0.52	.095	1.02
7	✱	99.79	0.21	.095	1.13
8	✕	99.80	0.20	.101	1.18

Figure 3. Particle Collection Efficiency versus Particle Size

VI. Conclusions

The test results on the UW Electrostatic Scrubber on the emissions from the Centralia coal-fired power boiler demonstrates the system's effectiveness for collecting particulates and sulfur oxides. The outlet concentrations from the UW Electrostatic Scrubber system were .00065 to .00459 grains/sdcf particulates and 10 to 510 ppm SO_2 depending on the inlet concentrations, operating parameters, and liquor alkalinity. With sodium carbonate liquor the SO_2 collection efficiency ranged from 41.1 to 97.4%.

VII. Acknowledgements

This research was supported by the US EPA (IERL) Research Grant (EPA Grant Nos. R-8-4393 and R-06035). The assistance, advice, and cooperation of our EPA Project officer, Dale A. Harmon is gratefully acknowledged. The assistance of University of Washington students and staff, Terrell Gault (whose MSE thesis research was on the effects of electrostatics on the sulfur dioxide collection efficiency), Tracey Steig, and Gary Raemhild is acknowledged. The cooperation and assistance of Pacific Power and Light Company personnel including Tom White, Ted Phillips, Bob Werner, Gary Slanina, Steve Lambert, Don Sakata, Al Seekamp, John Angelovich, and Pete Steinbrenner is greatly appreciated.

References

1. Kraemer, H. F. and H. F. Johnstone (1955). Collection of Aerosol Particles in the Presence of Electric fields. Ind. Engr. Chem. 47:2426.

2. Penney, G. W. (1944). Electrified Liquid Spray Dust Precipitator. U.S. Patent No. 2,357,354.

3. Pilat, M. J., Jaasund, S. A., and L. E. Sparks (1974). Collection of Aerosol Particles by Electrostatic Droplet Spray Scrubbers. Envir. Sci. & Tech. 8:340-348.

4. Pilat, M. J. (1975). Collection of Aerosol Particles by Electrostatic Droplet Spray Scrubbers. APCA Journal. 25:176-178.

5. Pilat, M. J. and D. F. Meyer (1976). University of Washington Electrostatic Spray Scrubber Evaluation. Final Report on Grant No. R-803278, EPA Report No. EPA-600/2-76-100 (NTIS No. PB 252653/AS).

6. Pilat, M. J., Raemhild, G. A., and D. L. Harmon (1977). Fine Particle Control with UW Electrostatic Scrubber. Presented at Second Fine Particle Scrubber Symposium, May 2-3, 1977, New Orleans.

7. Pilat, M. J., Raemhild, G. A., and D. L. Harmon (1977). Tests of University of Washington Electrostatic Scrubber at an Electric Arc Steel Furnace. Presented at Conference on Particle Collection Problems in the Use of Electrostatic Precipitators in the Metallurgical Industry, June 1-3, 1977, Denver.

8. Pilat, M. J. and G. A. Raemhild (1978). Control of Particulate Emissions with UW Electrostatic Spray Scrubber. Presented at EPA Symposium on the Transfer and Utilization of Particulate Control Technology, July 24-28, 1978, Denver.

9. Pilat, M. J., Raemhild, G. A. and A. Prem (1978). University of Washington Electrostatic Scrubber Tests at a Steel Plant. EPA Report No. EPA-600/7-78-177a, September 1978.

10. Pilat, M. J. and G. A. Raemhild (1978). University of Washington Electrostatic Scrubber Tests at a Coal-Fired Power Plant. EPA Report No. EPA-600/7-78/177b, December 1978.

11. Pilat, M. J., Raemhild, G. A., and T. W. Gault (1978). Tests on UW Electrostatic Scrubber for Particulate and Sulfur Dioxide Collection. Presented at Pacific Northwest International Section of Air Pollution Control Association meeting, November 9-10, 1978, Portland.

EPA MOBILE VENTURI SCRUBBER PERFORMANCE

Environmental Protection Agency Mobile Venturi Scrubber Performance - An empirical and modeling study of New Source Performance Standard-level venturi performance on pulverized coal boiler characteristics

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ABSTRACT

This report describes the Environmental Protection Agency's mobile venturi scrubber performance evaluation conducted at the power plants of Michigan State University, East Lansing, Michigan, and the City of Ames, Ames, Iowa. The effects of pulverized coal emission characteristics on venturi scrubber collectability are reported. Controlled variables were boiler operation, fuel type, and scrubber pressure drop. Use of a mathematical performance model provides support and insight into scrubber performance and measurement methodologies. Cost modeling data are shown for different boiler and scrubber characteristics for performance in the range of current and projected New Source Performance Standards.

The following highlights emerge from this study of conventional venturi scrubber performance on coal-fired boilers:

- Conventional venturi scrubber performance is cost-sensitive in the New Source Performance Standards' range of interest.
- Scrubber operation and performance characteristics are predictable with complete characterization and an improved computerized model.
- Scrubber operation, performance and cost levels are strongly dependent on influent fine particle concentration levels.
- Fuel type and/or boiler design are the primary factors for generation of fine particle concentration levels.
- Cofiring coal with refuse fuel increases fine particulate generation, causing dramatic increases in scrubber costs.

INTRODUCTION AND OBJECTIVE

This pilot scale venturi scrubber is one of three conventional particulate emission control devices mobilized by the Utilities and Industrial Power Division, Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency (UIPD/IERL/EPA), Research Triangle Park, North Carolina. The objective is to evaluate and compare the performance characteristics of a scrubber, baghouse and electrostatic precipitator (ESP) on industrial particulate emission sources. The purpose is to provide characteristic information and insight for appropriate selection of particulate control devices, in light of operation, performance, and cost considerations.

This report summarizes the results of mobile scrubber tests conducted at the power plants of Michigan State University, East Lansing, Michigan and City of Ames, Ames, Iowa over a 4-month period beginning July 1978. The particulate emission source at each site was a pulverized coal (PC) boiler; the Ames utility had refuse cofiring capability. The particulate-laden flue gas was slipstreamed and sampled at inlet and outlet locations of the scrubber by total mass measurements and Brink and Andersen cascade impactors. The test matrix was designed to study the effects of scrubber pressure drop and liquid-to-gas (L/G) ratio for different boiler/fuel cases. Scrubber performance and cost modeling generated the following:

- Comparison of empirical overall and fractional collection efficiencies with model predictions

- Comparison of experimental pressure drops with model predictions

- Scrubbing costs for tested boiler/fuel cases in New Source Performance Standards' (NSPS) range of interest (43 to 13 ng/J)

CONCLUSIONS

The following conclusions result from this study:

- Scrubbing costs become very sensitive to required performance levels; cost factors can range as much as 100-200 percent across the NSPS range of 43 to 13 ng/J (0.1 to 0.03 lb/million Btu).

- Boiler effluent characteristics are strongly dependent on fuel type and/or boiler design; differences in generated fine particle concentrations can impact scrubbing costs as much as 25-300 percent, dependent on required performance level.

- Cofiring coal with refuse fuel increases fine particle concentration; economic gains in fuel cost savings are offset by 10-80 percent cost penalties for scrubbing costs.

- The EPA/Calvert scrubber model was modified to incorporate two improvements:

1) The log-normal size distribution format was changed to accommodate a more realistic particle size-histogram format.

2) The effect of flue gas quenching in the venturi throat was mathematically defined, affording a more reasonable description of droplet formation, pressure loss and particulate collection.

- The model predicts venturi scrubber operation and performance with fair accuracy and precision; the model's accuracy is better for a 6 cm (2.3 in.) throat than a 3.5 cm (1.4 in.) throat, indicating appreciable wall effects for throat sizes less than 6 cm.
- For a given set of scrubber conditions, the model tends to: underpredict overall collection performance; underpredict the collection of fine particles (less than 2 μm); overpredict the collection of large particles (greater than 4 μm).
- The discrepancy between the model predictions and data can be attributed partly to measurement methodology, since the existing methodology does not account for differences in aerodynamic characteristics between the influent (dry) and effluent (wet) particles.

DESCRIPTION OF FACILITIES

Power Plants

Michigan State University (MSU) Power Plant 65. This power plant consists of three boilers designated as Units 1, 2 and 3. The pilot scrubber was tested on Unit 2 which is a 113,600 kg/hr (250,000 lb/hr) 30-35 MW boiler. The boiler fires pulverized Eastern Kentucky Coal (6 to 7 percent moisture, 8 percent ash, 0.75 percent sulfur, 29 million J/kg (12,500 Btu/lb)).

Ames Power Plant. Owned and operated by the city of Ames, this power plant consists of three boilers designated Units 5, 6 and 7. Scrubber tests were done on Unit 7 which is a 33 MW PC-fired boiler capable of firing up to 20 percent refuse-derived fuel (RDF). The plant uses a blend of 55 percent Iowa coal at 3 to 5 percent sulfur and 45 percent Colorado low-sulfur western coal. The heating value for the coal blend is 24.1 million J/kg (10,400 Btu/lb), compared to 13.9 million J/kg (6,000 Btu/lb) for the RDF.

Scrubber

The mobile scrubber facility is contained inside a standard freight trailer (12.2m x 2.4m, or 40 ft. x 8 ft.). It is equipped with three available venturi throats (3.5, 6.0, and 8.5 cm), a presaturator, a cyclone separator, and a baffled mist eliminator. Each venturi has a throat length of 30.5 cm and a radial water dumping nozzle 5.1 cm below the throat entrance. Appropriate auxiliaries and instrumentation are provided inside the trailer.

PROGRAM METHODOLOGY

Installation

Care was taken to ensure that a representative stream was withdrawn and delivered to the pilot scrubber. The slipstream was extracted isokinetically and transported isothermally to the pilot unit through heated ducting at velocities comparable to plant conditions. Inspection of the ducting after each test series revealed marginal dropout of particulate, due to either gravitational or centrifugal forces. At each test site, the slipstream was educted downstream of the air preheater and upstream of the pollution control device. For the Ames site, a second ducting was installed downstream of the full scale ESP.

Operation

The pilot scrubber was operated and tested on a daily start-up/shutdown basis. Equipment startup and system equilibrium were carried out in the morning, and performance measurements were conducted in the afternoon. There were indications of scaling at the wet/dry interface, a condition which warranted scale removal daily. Each set of inlet and outlet mass and impactor measurements were conducted concurrently. Sampling periods required 2-3 hour tests, enabling two sets of tests to be conducted daily. The scrubber liquor pH was maintained between four and six by adding a lime solution. The filtrate recycle-to-purge ratio was maintained at approximately 1:1 to restrict sulfate/sulfite accumulation.

Test Conditions

Table 1 summarizes scrubber test conditions and operating parameters. Pressure drops were varied from ~25 to 125 cm H_2O (~10 to 50 in. H_2O). Gas flowrates ranged from 7 to 16 am^3/min. (250 to 560 acfm). The liquid/gas (L/G) ratio was evaluated at 2 and 4 l/m^3 (15 and 30 gal/kcfm).

Data Acquisition

After setting the prescribed test conditions, the important operating parameters were recorded on a semihourly basis and included:

- Scrubber pressure drop
- Gas flowrate
- Scrubber liquor flowrate
- Gas temperature (before and after scrubber)
- Makeup water flowrate
- Scrubber liquor pH

On-site analyses of performance measurements were conducted to provide feedback on performance data and data quality.

Particulate Measurements

Total mass and impactor measurements at the inlet and outlet points were conducted at isokinetic conditions. Brink and Andersen impactors measured the inlet and outlet size distributions, respectively. Gelman glass fiber substrates were used at MSU, whereas Reeve Angel 934 AH material was preferred at Ames because of low SO_2 absorptivity. All substrates were preconditioned for 6 hours. Samples were obtained with extractive probes fitted with interchangeable nozzles at average velocity locations. Sampling trains similar to that described in Method 5 of the Federal Register were used.

Data Reduction

A computer program was used to calculate impactor stage cutpoints, particle size distributions and overall particulate loading. Fractional penetrations were calculated by a program that performs linear least square, quadratic least square and spline fits to log normal transformed inlet and outlet cumulative size distribution data.[1] This program was supplemented by manual graphical procedures whenever data showed excessive scatter.

The computer program for the scrubber model was applied to predict and compare scrubber operation and performance levels.[2] The original program was modified to accept inlet size distribution histograms and account for gas cooling in the venturi throat, assuming instantaneous quenching. The program's inlet requirements include seven parameters to define scrubber conditions and several descriptors for the influent particulate stream. The model then determines the fractional penetration relationship from the specified conditions to--

1) relate the influent size distribution for the prediction of the effluent size distribution, and

2) integrate the influent size distribution to predict the effluent particulate concentration.

RESULTS AND DISCUSSION

Overall Collection Performance

The control device characteristic of practical importance is that of overall collection performance. This performance can be described and measured by the emission level which penetrates the device and passes into the atmosphere. Emission levels are used by the regulatory agency to stipulate NSPS. The scope of this report entails venturi scrubber performance and costs in the range of current and projected NSPS for coal-fired utility boilers. Analyses were made for NSPS levels of 43 and 13 ng/J, and for an intermediate emission level of 21.5 ng/J, respectively.

Scrubber performance levels as a function of pressure drop are shown in Figure 1 for the three fuel types studied. Two performance curves for each fuel case are included, comparing results from the empirical data and computerized model. The three model curves methodically reflect distinct performance requirements for the three fuel cases. The fuel-specific performance relationships should be considered realistic since they account for measured differences in influent size distributions. These performance relationships are presented over the range of current and projected NSPS.

A correspondence between the model and data curves is observed (Table 2), although the model results are consistently overpredictive to the data. The spread between the data curves is more apparent than between the model curves due to appreciable wall effects in pilot scale venturis discussed below. Considering that better data/model correlations have been shown by others, scrubber performance can be described or bracketed by the paired curves in Figure 1.[3,4]

Particle Size Collection Performance

Analysis of particle size collection performance (i.e., fractional efficiency or fractional penetration) offers support of and insight into overall collection performance. As technological advances are being made, it is becoming appropriate to evaluate performance in terms of penetration, rather than collection. In this text, fractional penetration is used to describe particle size collection performance.

This study was conducted on three different fly ash species with two venturi throat sizes. Figures 2 through 6 compare fractional penetration curves predicted by the model with the data for various pressure drops and L/G ratios. Most of the data are for the 6 cm throat; the results for the 3.5 cm throat are noted in Figures 5 and 6. The graphs show a fair comparison between the model predictions and the empirical data. The following peculiarities are worth noting:

- The data are skewed with respect to the model with recurring similarity.
- In general the model overpredicts penetration for particles below 2 microns aerodynamic diameter.
- The model generally underpredicts penetration for particles above 4 microns aerodynamic diameter.
- In the middle of the particle size range, model and data curves intersect, showing better correlation.
- The degree of correlation is higher in the case of the 6.0 cm venturi as compared to the 3.5 cm venturi.

These discrepancies/peculiarities are somewhat accountable in that there are several difficulties in measuring scrubber effluent size distribution, including:

- Concentration of particulate is reduced,
- most of the penetrated material is composed of fine particulate,
- saturation conditions occur with the presence of penetrated and re-entrained droplets, and
- the particle species measured as the effluent is distinct from the dry species measured as the influent.

For the first three difficulties listed, procedural improvements can be made to resolve or minimize the complications. However, the problem of comparing dry fly ash size concentrations to wet fly ash size concentrations requires further analysis. Demonstration of the anomalous effects attributable to this dry/wet phenomenon are shown by the hypothetical diagrams in Figure 7.

Pressure Drop

Figures 8 and 9 compare experimental and predicted pressure drops for the 6 cm venturi. MSU data show excellent correlation, whereas Ames data show the model slightly overpredicts the pressure drop. However, the model overpredicts pressure drop by about 100 percent for the 3.5 cm venturi (Table 3). This reiterates the need to completely account for scrubber geometry, throat size and wall effects in pilot scale venturis.

The above predictions for fractional collection efficiency and pressure drop assume instantaneous quenching of flue gas to outlet conditions upon contact with scrubber water. The predictions by quench-corrected modeling give higher penetration in small particle range and lower penetration in large particle range (the difference being less than 10 percent for each particle size, and about 30 percent less pressure drop for tested scrubber conditions).

Scrubber Influent Characteristics

The fractional collection in a venturi scrubber is a function of particle diameter, and hence overall penetration is a strong function of inlet particle size distribution. The average inlet particle size distributions are plotted in Figure 10 with fuel type and slipstream location as parameters. The overall particle concentration for each case is also tabulated.

Particular attention should be drawn to the comparison of these size curves in the fine particle range. The apparently small divergence of the three size curves below 2 μm corresponds with substantial differences in outlet loading. The Ames case in which coal plus 20 percent RDF were fired shows the highest concentration of fine particulate, whereas the MSU case offers the lowest concentration.

Effluent concentrations with operating pressure drop for the three fuel cases are presented in Figure 1. Comparison of the two extreme cases in fine particle concentration show that pressure drop requirements can vary from

- 25 to 35 cm at the NSPS level of 43 ng/J, and
- 40 to 140 cm at the NSPS level of 13 ng/J

These dramatic differences in pressure drop were generated by the model, and were supported by the empirical particle size and concentration results. The cost impact of these results will be discussed later.

Effect of L/G Ratio

At MSU, scrubber tests were conducted for two L/G ratios (2 and 4 l/m^3) to study their effect. Figure 11 presents the data and model predictions. The model shows that a L/G ratio of 4 l/m^3 gives inferior scrubber performance. The data do not show an equally dramatic difference, but they do show qualitative agreement. Calvert, et al. have shown that the optimum L/G range is 1-2 l/m^3, which supports these results.[5]

Scrubber Performance as a Secondary Device

In Ames, the scrubber was also tested as a secondary device slipstreaming downstream of a full scale ESP. Figure 12 shows data and model predictions. The results are fairly similar to the case in which the scrubber operates upstream of the ESP. These results, along with Reference 4, indicate that particle collection by a venturi scrubber is not affected by an upstream ESP.

Cost Analysis

The cost analysis objective was to obtain an estimate of scrubbing costs in the NSPS range. The analysis is based on the following factors:

The analysis is based on the following factors:

1. Emission source is 350 MW PC boiler.
2. Flue gas flow rate is 130 acm/min per MW at 177°C.
3. Flue gas is treated in three parallel modular venturi scrubbers.
4. Sludge treatment involves clarification, filtration and land-filling.

Capital, operating and maintenance costs for three scrubber systems designed to operate at 25.4, 76.2, and 127 cm (10, 30, 50 in.) pressure drop, respectively, are summarized in Table 4. The capital costs have been annualized, assuming an equipment life of 10 years and an annual discount rate of 8 percent. Annualized capital costs are added to annual O & M costs to obtain scrubbing cost per kW-h energy. Scrubbing costs in mils/kW-h are plotted against scrubber pressure drop in Figure 13. This figure in conjunction with Figure 1 gives scrubbing costs as a function of emission level for each fuel type, as plotted in Figure 14.

Scrubber costs for various emission levels are shown in Figure 14. This figure shows that for NSPS, 43 ng/J (0.1 lb/million Btu) scrubbing costs are between 2.6 to 3.1 mils/kW-h. The costs increase slightly to 3.1 to 4.1 mils/kW-h for emission level 21.5 ng/J (0.05 lb/million Btu). Between 21.5 and 13 ng/J 0.03 lb/million Btu) costs increase exponentially, resulting in a 6.4 to 9.2 mils/kW-h cost estimate for the 13 ng/J NSPS level.

The range of costs associated with the above emission levels reflect the cost impact of the range of fly ash characteristics encountered in this study. The cost range for the three levels increases for decreasing levels because of the exponential nature of the cost/performance relationship. As evidenced by this cost range, scrubber performance and cost become specific and sensitive to boiler/fuel types.

From this performance/cost analysis, the following conclusions can be drawn:

- Venturi scrubbing can be considered a competitive control option for an emission level range of 21.5 to 43 ng/J for particulate and gaseous control.
- For the emission range below 21.5 ng/J, venturi scrubbing costs rise dramatically, indicating scrubbing becomes less cost-attractive in this range.
- As NSPS levels become stricter, selections of coal/boiler types become increasingly cost sensitive considerations for venturi scrubbing.

REFERENCES

1. Lawless, Phil A. Analysis of Cascade Impactor Data for Calculating Particle Penetration. EPA - 600/7-78-189, U. S. Environmental Protection Agency, Washington, DC, September 1978. 39 p.

2. Yung, S. C., S. Calvert, and H. F. Barbarika. Venturi Scrubber Performance Model. EPA - 600/2-77-172, Research Triangle Park, NC, August 1977. 197 p.

3. Ramsey, G. H., L. E. Sparks, and B. E. Daniel. Experimental Study of Particle Collection by a Venturi Scrubber Downstream from an Electrostatic Precipitator. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Volume 3. Scrubbers, Advanced Technology, and HTP Applications. EPA - 600/7-79-044c, U. S. Environmental Protection Agency, Washington, DC, February 1979. p. 161-177.

4. McCain, Joseph D. CEA Variable - Throat Venturi Scrubber Evaluation. EPA - 600/7-78-094, U. S. Environmental Protection Agency, Washington, DC, June 1978. 75 p.

5. Yung, S., H. Barbarika, S. Calvert, and L. Sparks. Venturi Scrubber Design Model. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Volume 3. Scrubbers, Advanced Technology, and HTP Applications. EPA - 600/7-79-044c, U. S. Environmental Protection Agency, Washington, DC, February 1979. p. 149-159.

Acknowledgements

This program was sponsored by the Utilities and Industrial Power Division, Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency (UIPD/IERL/EPA), Research Triangle Park, North Carolina.

The authors express sincere appreciation to the following individuals for their involvement with and contributions toward this program:

- Dale Harmon, Les Sparks, and James Turner of IERL/EPA, Research Triangle Park, North Carolina.
- Robert Olexsey of IERL/EPA, Cincinnati, Ohio.
- Joe Kavanaugh of Michigan State University Power Plant, East Lansing, Michigan.
- Merlin Hove of Ames Power Plant, Ames, Iowa.
- Fred Hall, John Bruck, and Diane Albrinck of PEDCo Environmental, Inc., Cincinnati, Ohio.

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Table 1 SCRUBBER TEST CONDITIONS AND OPERATING PARAMETERS

Parameter	MSU	Ames
1. Fuels Tested	Coal	Coal only and coal + 20 percent RDF
2. Mode	As primary device	As primary and secondary device
3. Venturis Tested	3.5 and 6 cm	6 cm
4. L/G Ratio	2 and 4 $1/m^3$ (15 to 30 $gal/1,000\ ft^3$)	2 $1/m^3$ (15 $gal/1,000\ ft^3$)
5. Pressure Drops	cm of W.C. (in. of W.C.)	cm of W.C. (in. of W.C.)
3.5 cm Throat ($L/G = 2\ 1/m^3$)	101.6, 127 (40, 50)	
6.0 cm Throat ($L/G = 4\ 1/m^3$)	25.4 to 127 (10 - 50)	
6.0 cm Throat ($L/G = 2\ 1/m^3$)	20.3 to 76.2 (8 - 30)	25.4 to 76.2 (10 - 30)
6. Gas Flow Rate Acm/m (acfm)	8.5 - 10.8 (301 - 380)	7.22 - 15.9 (255 - 560)
7. Water Flow Rate 1/m (GPM)	15.9 - 30.2 (4.2 - 8.0)	12.5 - 30.2 (3.3 - 8.0)
8. Throat Velocity m/sec (ft/sec)	43.8 - 157.2 (144 - 516.0)	42.6 - 93.6 (140 - 307.0)
9. Temperature before venturi (Inlet) °C	131° - 182°	149° - 168°
10. Temperature before Mist - Eliminator (Outlet) °C	90° - 139°	103° - 156°

Table 2 SCRUBBER PRESSURE DROP AND COST REQUIREMENTS AT THREE PERFORMANCE LEVELS

	Performance Level	43 nanograms/joule		21.5 nanograms/joule		13 nanograms/joule	
SNO	Parameter	Scrubber ΔP cm W.C.	Scrubbing Cost mils/kW-h	Scrubber ΔP cm W.C.	Scrubbing Cost mils/kW-h	Scrubber ΔP cm W.C.	Scrubbing Cost mils/kW-h
1.	Ames-RDF-Data	20.3	2.76	35.0	3.1	114.3	6.7
2.	Ames-RDF-Model	35.6	3.12	67.0	4.06	152.4	9.2
3.	Ames-Coal-Data	7.62	2.52	20.0	2.7	53.3	3.58
4.	Ames-Coal-Model	25.4	2.88	50.0	3.48	135.0	8.16
5.	MSU-Coal-Data	5.08	2.50	18.0	2.7	30.48	3.04
6	MSU-Coal-Model	15.2	2.64	37.0	3.16	109.2	6.4

Table 3 COMPARISON OF EXPERIMENTAL AND PREDICTED PRESSURE DROP (MSU)

3.5 cm Throat

Test ID	ΔP - Experimental cm W.C.	ΔP - Predicted cm W.C.
A1	101.6	173
A2	101.6	185
A3	101.6	185
A4	101.6	226
A5	101.6	225
B1	127.0	253
B2	127.0	253
B3	127.0	243
B4	127.0	249

Table 4 SUMMARY OF COSTS

All Costs in December 1979 dollars

SNO	Parameter	Case A	Case B	Case C
1.	Scrubber pressure drop cm W.C.	25.4	76.2	127
2.	Scrubber and auxiliary equipment capital cost on turnkey basis. (excluding sludge treatment plant)	$ 6,738,800	$ 12,355,500	$ 18,579,100
3.	Operating and maintenance costs. (per annum)	2,081,800	3,453,800	5,352,700
4.	Capital cost of sludge disposal system.	6,443,000	6,443,000	6,443,000
5.	Operating cost of sludge disposal system. (per annum)	4,145,000	4,145,000	4,145,000
6.	Total capital costs (2 + 4)	13,182,000	18,799,000	25,022,000
7.	Total operating and maintenance costs. (per annum) (3 + 5)	6,227,000	7,599,000	9,497,700
8.	Uniform annual equivalent of capital cost at 8 percent discount and 10 years equipment life (Ref. 4, page 4-89 and Table A-8)	1,965,000	2,801,000	3,729,000
9.	Uniform annual equivalent of capital cost. (mils/kW-h)	0.67	0.95	1.27
10.	O & M costs (mils/kW-h)	2.11	2.58	3.23
11.	Scrubbing costs (mils/kW-h) (9 + 10)	2.88	3.53	4.5
	percent of 4 ¢/kW-h energy cost	7.2	8.8	11.25

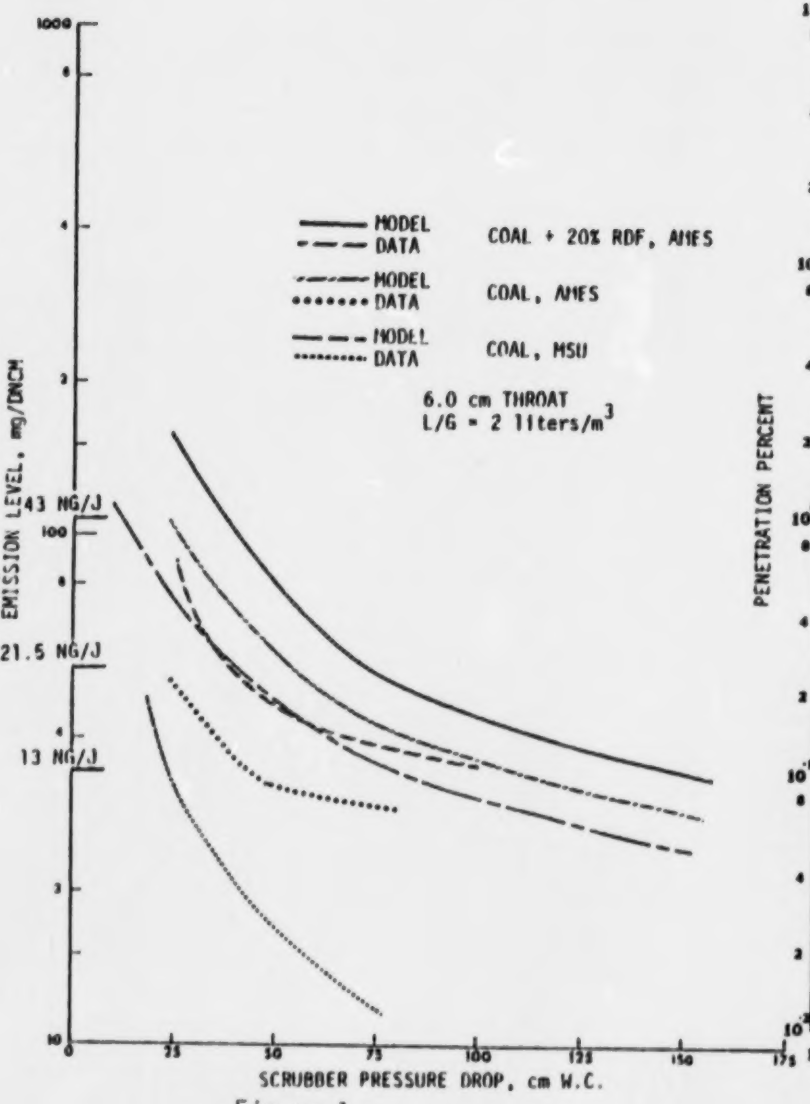

Figure 1
Comparison of predicted scrubber effluent particulate concentration with data.

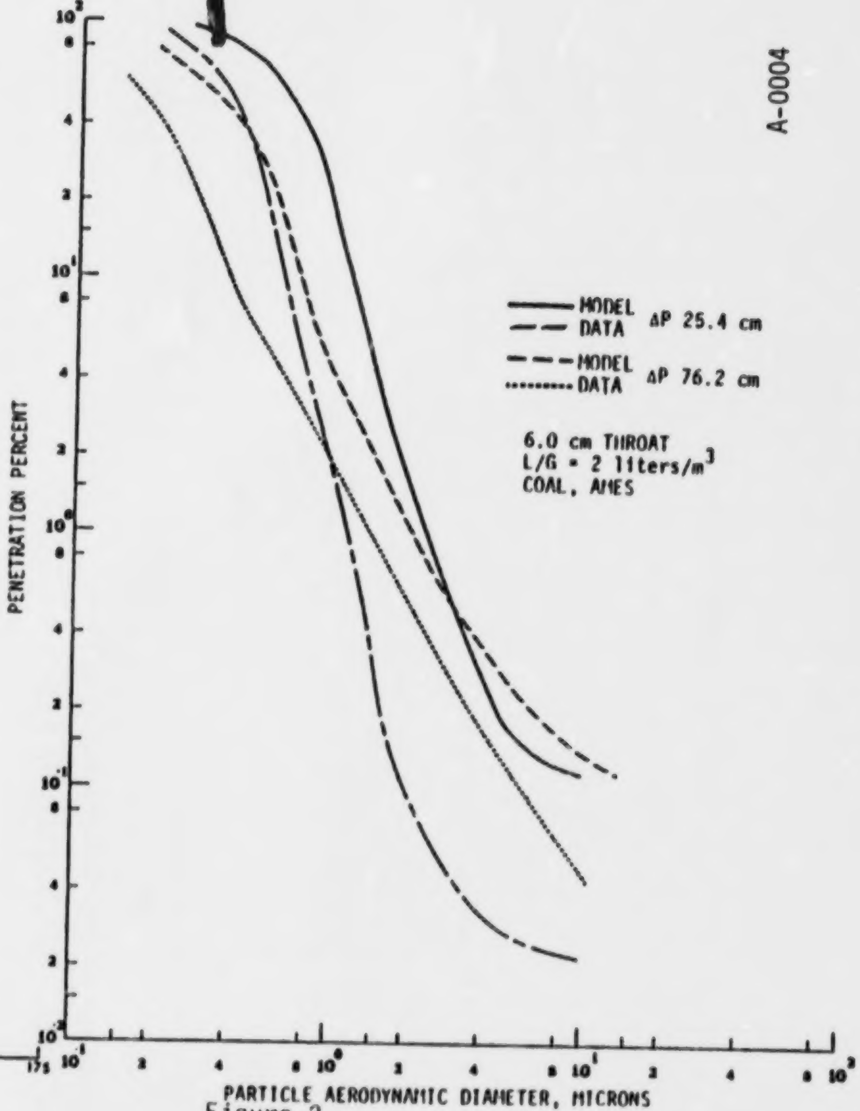

Figure 2
Comparison of predicted fractional penetrations with data for pulverized coal at Ames.

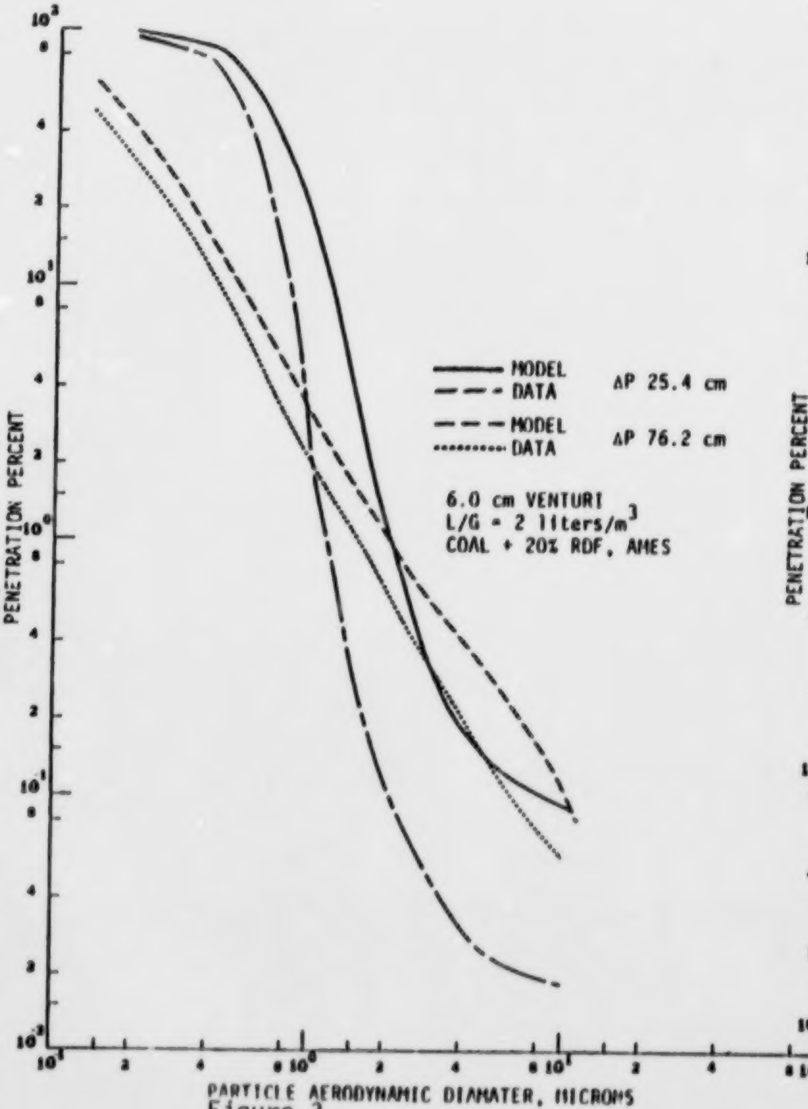

Figure 3
Comparison of predicted fractional penetrations with data for pulverized coal plus 20% RDF at Ames.

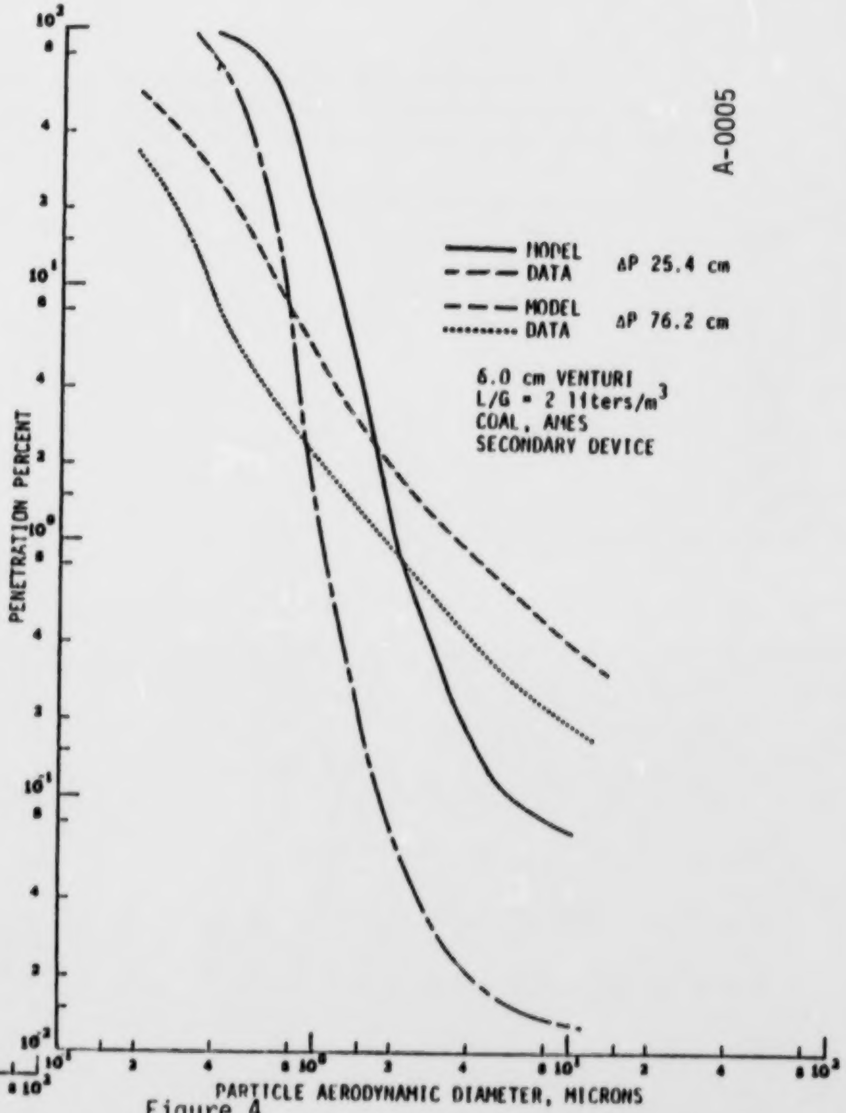

Figure 4
Comparison of predicted fractional penetrations with data for pulverized coal at Ames, scrubber operating as secondary device downstream of full scale ESP.

A-0005

A-0006

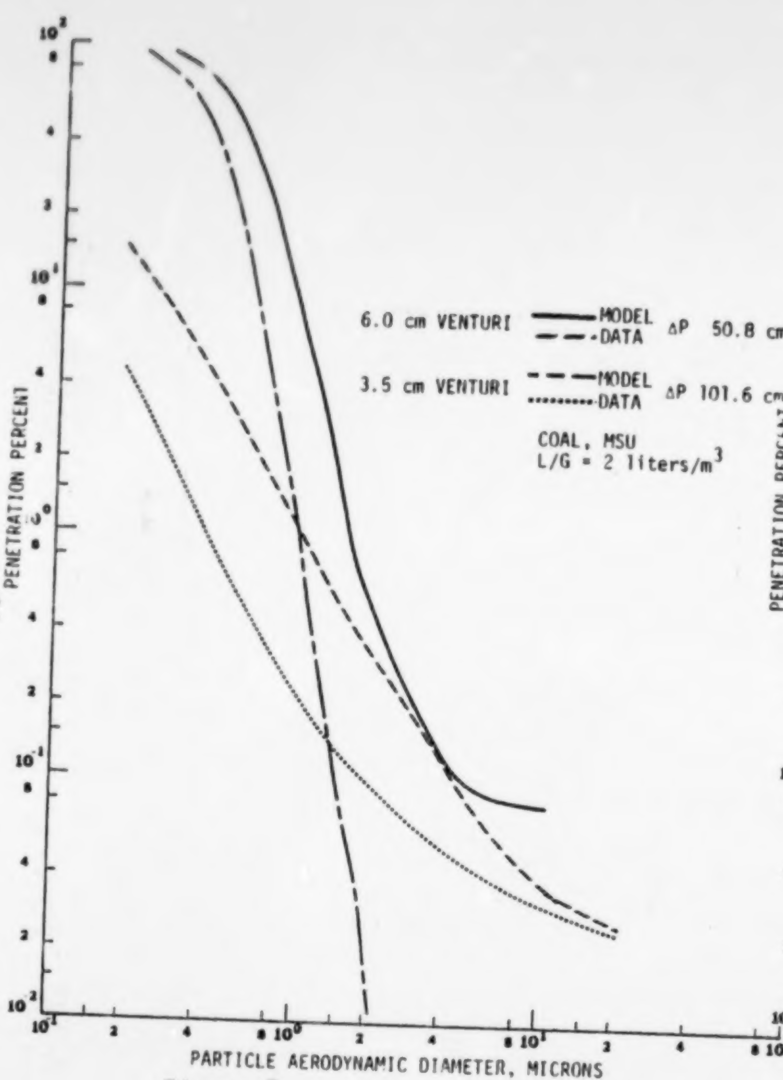

Figure 5
Comparison of predicted fractional penetrations with data for pulverized coal at Michigan State University.

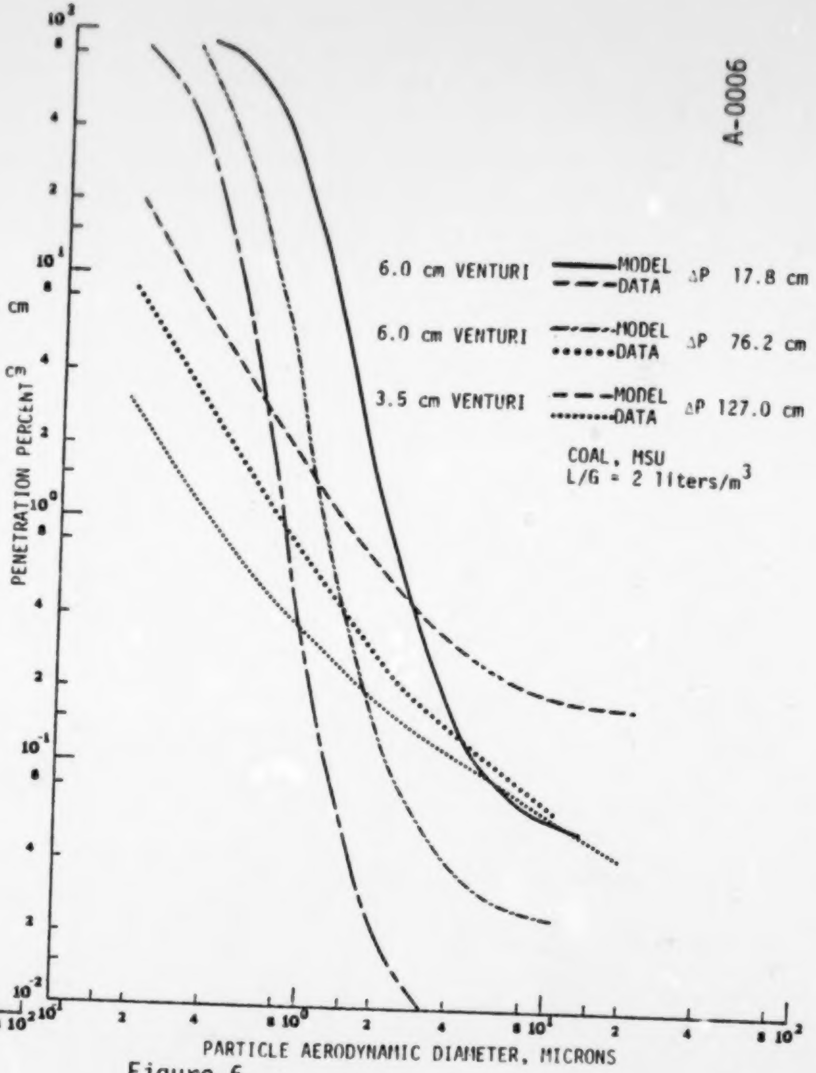

Figure 6
Comparison of predicted fractional penetrations with data for pulverized coal at Michigan State University.

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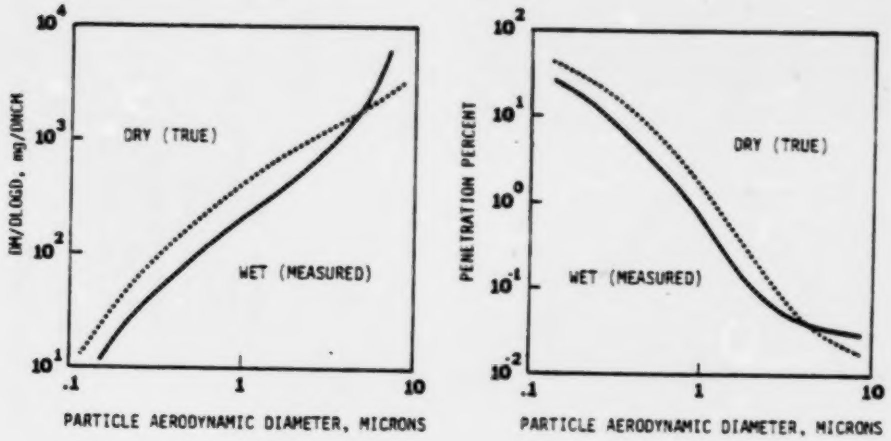


Figure 7 A schematic representation of wet-particle effect.

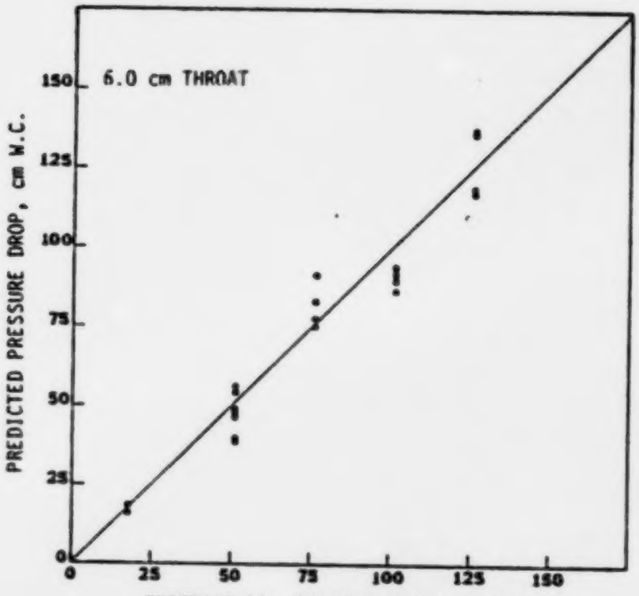


Figure 8 Comparison of predicted and experimental scrubber pressure drop at Michigan State University.

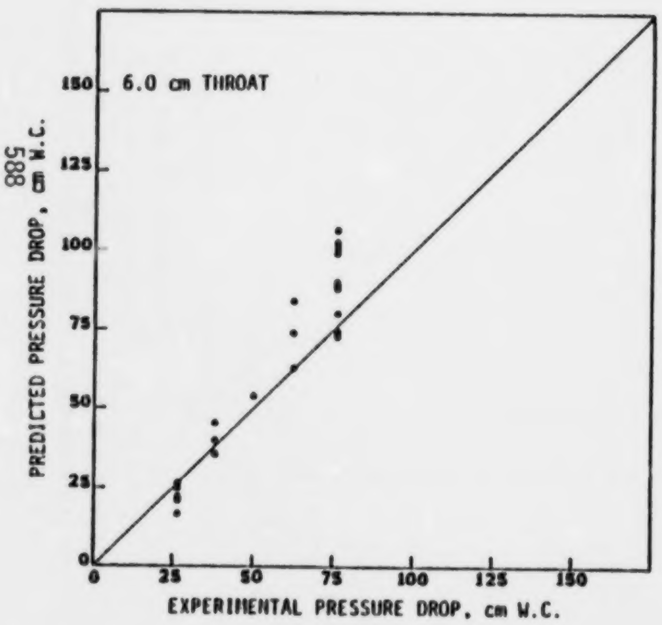
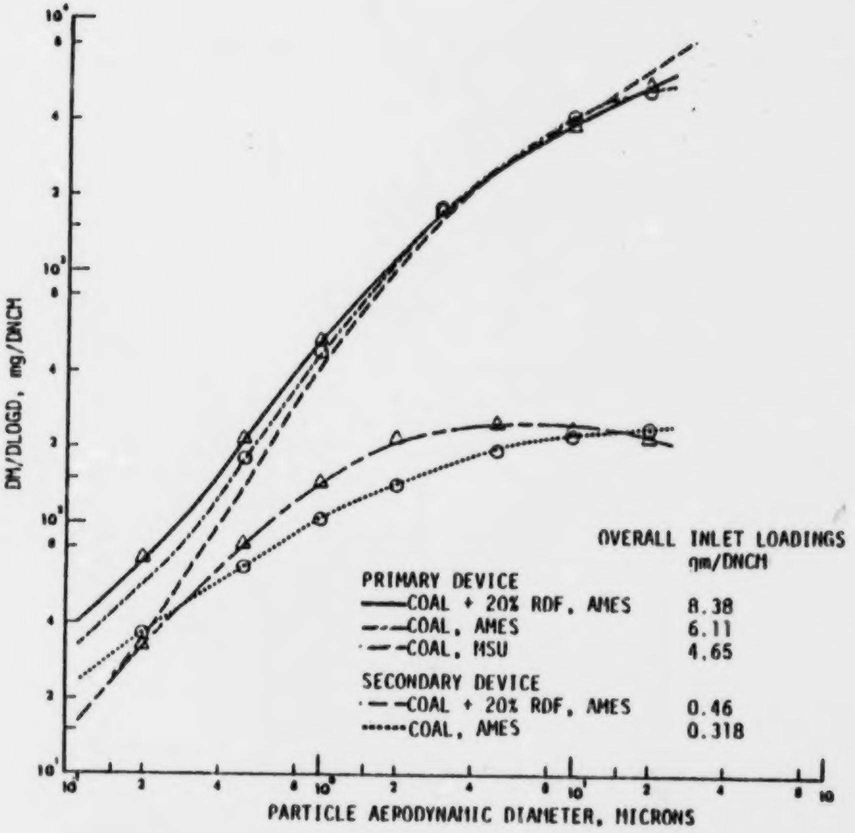


Figure 9 Comparison of predicted and experimental scrubber pressure drop at Ames.



	OVERALL INLET LOADINGS gm/DNCM
PRIMARY DEVICE	
——COAL + 20% RDF, AMES	8.38
—·—COAL, AMES	6.11
·——COAL, MSU	4.65
SECONDARY DEVICE	
·— —COAL + 20% RDF, AMES	0.46
······COAL, AMES	0.318

Figure 10 Average inlet particle size distributions and overall loadings.

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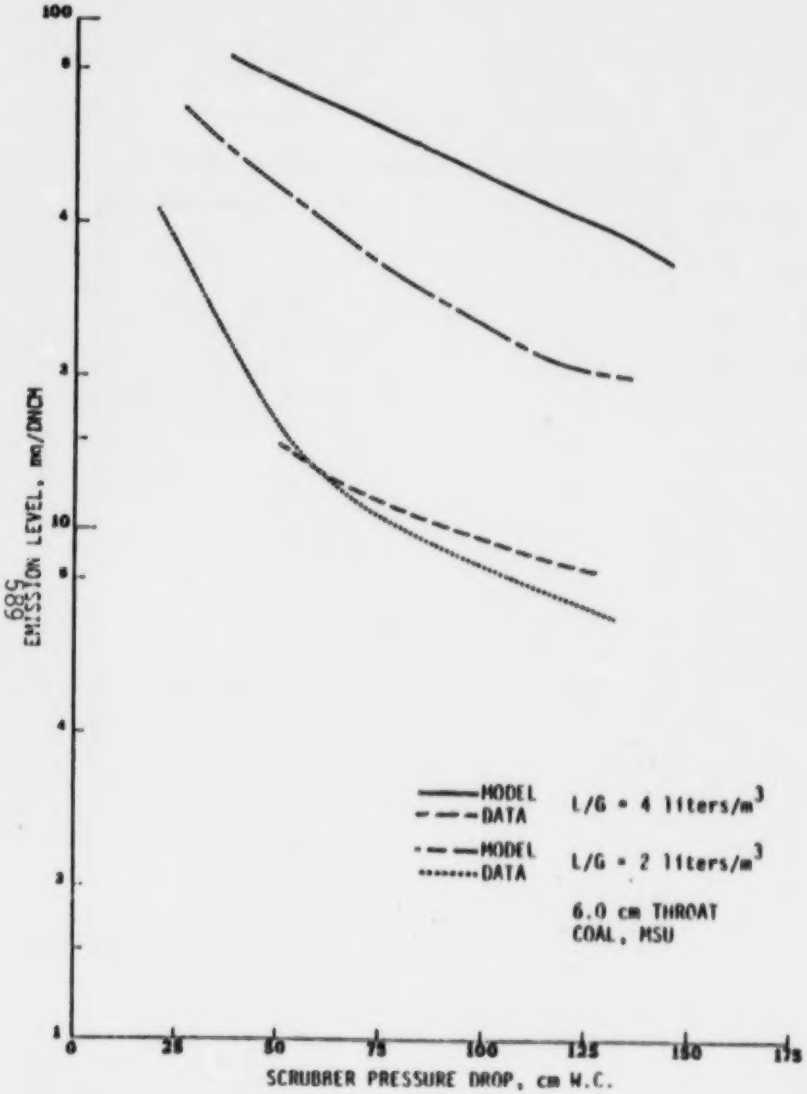

Figure 11 Effect of L/G ratio on scrubber performance.

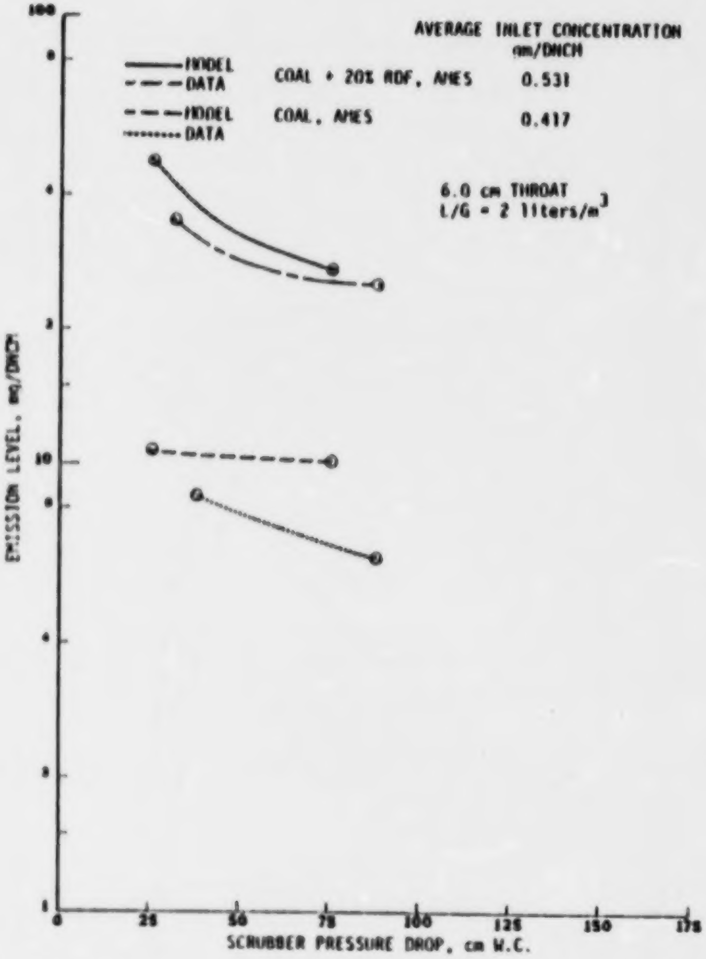

Figure 12 Scrubber performance as a secondary device.

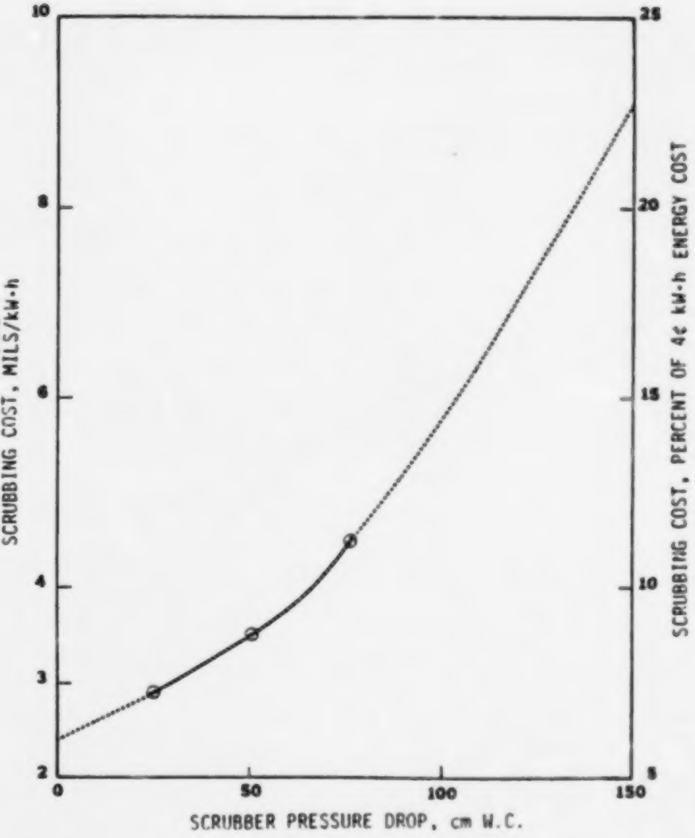

Figure 13 Scrubbing cost per kW·h as a function of pressure drop.

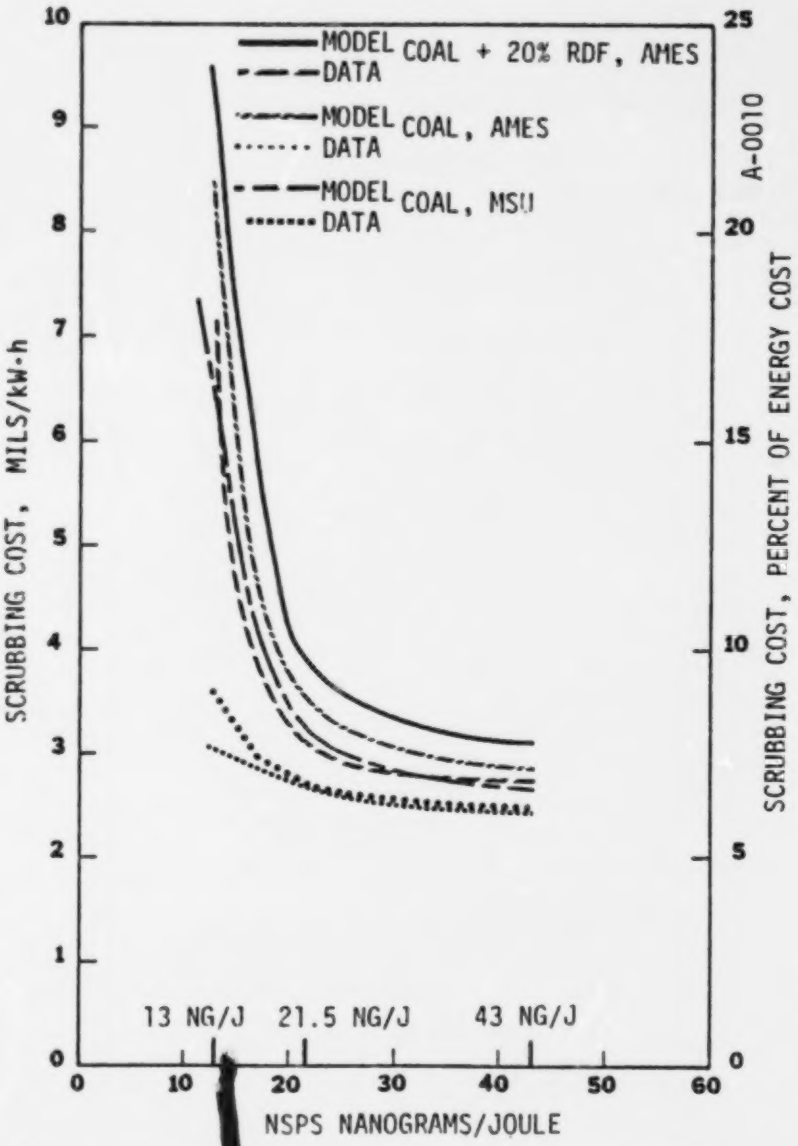

Figure 14 Scrubbing cost per kW·h as a function of NSPS.

THE RESULTS OF A TWO-STAGE SCRUBBER/ CHARGED PARTICULATE SEPARATOR PILOT PROGRAM

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ABSTRACT

Until recently, the two-stage wet scrubbing system (a venturi followed by an SO_2 absorber) has been successful in meeting the old EPA particulate matter and SO_2 emission levels. However, the two-stage scrubber may have limited application because of the power required to meet the new EPA particulate emission standards.

With this in mind, Combustion Engineering developed a new wet scrubbing concept: a two-stage scrubber that incorporates a charged particulate separator (wet precipitator).

To demonstrate performance and obtain design data, a test program was conducted at a Midwestern utility.

This paper presents the test results, a conceptual design for a full-size unit, and an economic evaluation that will show the potential for this unique system to meet the new EPA requirements.

THE RESULTS OF A TWO-STAGE SCRUBBER/ CHARGED PARTICULATE SEPARATOR PILOT PROGRAM

INTRODUCTION

In the past decade, the EPA standards for emissions from stationary sources have gradually become more stringent. To meet today's standards, Combustion Engineering, Inc. developed an improved scrubbing concept, the Two Stage Plus. The Two Stage Plus, which is a low pressure drop rod scrubber (venturi), followed by a spray tower absorber and a charged particulate separator, is capable of meeting the new EPA requirements without restriction on the quality of coal.

Additionally, the Two Stage Plus is economically attractive compared to a conventional dry collector followed by a wet SO_2 absorber. Its attractiveness is demonstrated by its low capital and operating costs over a wide range of sulfur and ash contents in the coal.

Compared to the dry scrubbing concept, the "Two Stage Plus" is economically favorable with Western coals (which produce alkaline flyash), even with sulfur content in the coal as low as 0.7%.

BACKGROUND

Prior to June 1979, the EPA emission standards for power plants were 0.1 lb/10^6 Btu for particulate and 1.2 lb/10^6 Btu for SO_2.(1) To meet these standards, Combustion Engineering offered two concepts for particulate and SO_2 removal: a two-stage scrubber system and an electrostatic precipitator followed by an SO_2 absorber. The two stage system is comprised of a rod scrubber (venturi) followed by a spray tower absorber with an integral mist eliminator and reheater. The rod scrubber is designed to remove mostly particulate and a fraction of SO_2, whereas the spray tower is designed to remove mostly SO_2 and a small fraction of particulate.

For most coals, particulate emission from the two stage scrubbing and the ESP/SO_2 absorber has generally been below the EPA requirement. The particulate emission level achieved was less than 0.08 lb/10^6 Btu at Northern States Power's Sherburne County Units 1 and 2 (two-stage system), less than 0.04 lb/10^6 Btu at The Kansas Power and Light Company's Lawrence 4 (two-stage system), and less than 0.04 lb/10^6 Btu at Louisville Gas and Electric Company's Cane Run 5 (ESP followed by an SO_2 absorber). See Kruger (1977),[2] Green and Martin (1977),[3] Green et. al. (1978),[4] and Van Ness et. al. (1979).[5]

In June 1979, EPA issued new emission standards. The proposed standards will limit the emission of particulate matter from steam generators that fire more than 250 x 10^6 Btu/hr (73 megawatts) of fossil fuel. The particulate emissions are limited to 13 nanograms/joule heat input (0.03 lb/10^6 Btu) and must be reduced 99% from uncontrolled emission levels. In the case of SO_2, the following three conditions must be satisfied:

a) SO_2 emission must not exceed 520 ng/J (1.2 lb/10^6 Btu).

b) SO_2 must be reduced 90% from uncontrolled emission levels, unless

c) the emission level is 250 ng/J (0.6 lb/10^6 Btu) or less, in which case a sliding scale of removal efficiency applies down to a level of 0.2 lb/10^6 Btu, at which level and below a 70% minimum removal is required.

Presently, C-E offers several design concepts that have the capability of achieving the new EPA SO_2 and particulate emission requirements. These concepts are:

The Two Stage Wet Scrubbing

This concept can achieve EPA's new particulate requirements; however, it requires a relatively high pressure drop depending on the flyash characteristics and, therefore, its effectiveness is limited to certain coals.

ESP/Single Stage Wet Scrubber

With proper design of the ESP, this system can meet the EPA particulate emission requirements. This system may be costly, depending on the flyash characteristics, especially if requiring a precipitator SCA of greater than 500 to 600.

Dry Absorber Particulate Collector

This concept can achieve the EPA particulate requirement, but has not been demonstrated in full size and may not be practical with high sulfur coals.

THE TWO STAGE PLUS CONCEPT

In an effort to meet the EPA emission requirement without restriction on the quality of coal, C-E has developed a modified two-stage scrubber, Two Stage Plus. The Two Stage Plus is comprised of a low pressure drop rod scrubber (venturi) followed by a spray tower and a "Charged Particulate Separator" (CPS) based on the concept of wet precipitation. The offering of this concept is predicated on C-E's long and successful experience with two-stage scrubbing and wet precipitators. Two-stage scrubbing using the rod design has demonstrated success in terms of performance and availability. The rod scrubber has been used in AQCS installations totalling over 2000 megawatts of generating capacity. The two-stage system at NSP's Sherburne County Units 1 and 2, representing 1520 MW, has been in operation for 3½ years. Component development and material evaluation during this period has resulted in design improvements to the rod scrubber.

The charged particulate separator (CPS) has been designed as a wet electrostatic precipitator, which was demonstrated on a full size unit in Bressoux, Belgium over 16 years ago. The wet ESP was installed behind a wet filter. The wet filter is similar to C-E's rod scrubber except that the flow is horizontal. The design fuel for this application was as follows:

Sulfur	0.85%
Moisture	14.0
Ash	29.0
Volatiles	13.0
Carbon	44.0

Tests conducted in June, 1976 (13 years after start-up) by an independent Belgium laboratory showed that the particulate collection efficiency of the wet precipitator was 90%. The design gas volume for the wet precipitator is 100 cubic meters per second (211, 765 ACFM). The water spray system is designed for two level application. Below the precipitator, water is sprayed against the gas flow at a rate of 20 cubic meters per hour (80 GPM). Above the precipitator the spray was intermittent at the rate of 60 cubic meters per hour (264 GPM). During cleaning, the precipitator voltage level is reduced to avoid heavy sparking and power arcing.

The shell and ductwork are rubber-coated mild steel and internal parts are stainless steel. There has been no significant corrosion of the precipitator during 16 years of operation.

The use of the wet electrostatic precipitator preceded by an SO_2 absorber for particulate removal, as opposed to a conventional dry ESP was necessitated at that time by the stringent Belgium emission requirements. These requirements limited particulate and SO_2 emission to very low levels. Since then, however, the European SO_2 emission limits have been relaxed precluding the need for the SO_2 absorber. As a result, the SO_2 absorber/wet ESP became economically less attractive than a dry ESP for particulate removal only and is no longer a practical design in Europe.

TWO STAGE PLUS BENEFITS

To demonstrate the benefits of the Two Stage Plus, it will be compared to several other flue gas desulfurization techniques. These techniques include: the two-stage scrubber (venturi for particulate collection followed by an SO_2 absorber), a cold ESP for particulate collection followed by an SO_2 absorber, and finally the dry SO_2 absorber followed by a particulate collector.

The charged particulate separator in the Two Stage Plus is much smaller that a conventional cold ESP because:

1) To meet the EPA limits the CPS requires a low particulate removal efficiency compared with the ESP. This is due to precollection in the rod scrubber, which causes the particulate at the CPS inlet to become small compared with the ESP inlet, 0.10 vs. 7 $lb/10^6$ Btu.

2) The gas treated in the CPS is saturated and is relatively cold (130 F), thereby resulting in conditions favorable for particulate collection. The gas treated in the ESP on the other hand is drier and hotter (300 F). Both conditions tend to increase the resistivity of the ash reducing the ability of the ESP to collect ash.

3) Because of the lower gas temperature, the volumetric flow through the CPS is smaller than flow through the ESP.

4) Re-entrainment of the ash deposit is usually a major consideration in choosing the right gas velocity for an electrostatic precipitator. Since the charged particulate separator (CPS) operates in a wet environment, the deposit on the collecting electrodes is wet, and therefore, more difficult to re-entrain. As a result, it is usually safe to operate the CPS at gas velocities higher than usually required in a conventional ESP.

Calcium compounds are commonly present in varying concentrations and degrees of alkalinity in the flyash. If an ESP is used ahead of an SO_2 absorber, the flyash with its calcium is collected and sent to disposal. If allowed in the scrubber, these calcium compounds can be very useful in absorbing SO_2. In the Two Stage Plus, all the ash generated by the furnace can be used in absorbing SO_2. Thus the addition of supplementary limestone is minimized, resulting in significant operating cost savings.

In a conventional two-stage scrubber, the pressure loss across the venturi, is usually set at high levels (15-20 in. w.g.) to achieve high particulate removal efficiency. In the Two Stage Plus, where the venturi acts only as a precollecting device, the pressure loss is much lower (3-5 in. w.g.). As a result, the operating cost of the Two Stage Plus will be reduced significantly.

The charged particulate separator has been successfully used in various applications as a high efficiency mist eliminator. The mechanism for removing mist in the CPS is similar to that for dust in an electrostatic precipitator. With its mist removal capability, the CPS precludes the need for a fine mist eliminator, which is usually required in conventional SO_2 scrubbers.

The Two Stage Plus collects particulate and SO_2 in one system. This is because the particulate collection stage and the SO_2 absorber stage both discharge into a common disposal system. In contrast, systems that require dry precollectors such as an ESP followed by a wet scrubber require two waste disposal systems. The single disposal system is simpler than the double disposal system since it includes fewer components to operate and maintain.

Unlike some concepts, such as dry scrubbing, where SO_2 removal is limited at high sulfur levels, the two stage plus is capable of removing SO_2 to any required emission level for any sulfur level in the coal. More importantly, the additive consumption is only slightly above the theoretical requirement. The additive consumption for the dry absorber on the other hand is significantly higher than the theoretical requirement, especially with high sulfur conditions.

PILOT PLANT TEST PROGRAM

Pilot Plant Description

To demonstrate the capability of the Two Stage Plus, a pilot plant was installed at Northern States Power Company, Sherburne County Plant. The purpose of the pilot program is:

1) To demonstrate that a particulate emission level of (13 ng/J) 0.03 $lb/10^6$ Btu can be achieved.

2) To determine a method of maintaining the CPS in a clean state that will not hinder performance.

3) To develop design criteria for a full-size system.

The 10,000 cfm pilot plant was installed at the 730-MW NSP's Sherburne County Unit 1. The fuel fired was Sarpy Creek coal. The coal and ash analyses are shown in Tables 1 and 2. The air quality control system at Unit 1 consists of 11 (+1 spare) scrubber modules. Each module consists of a rod scrubber (venturi) and a marble bed, a mist eliminator and a reheater.

TABLE 1 TWO-STAGE PLUS PILOT PLANT
COAL PROXIMATE ANALYSIS

	Mean
Moisture	23.9%
Ash	10.8%
Volatile Matter	27.7%
Carbon	37.6%
Sulfur	1.0%
Heating value	8300 Btu/lb.

TABLE 2 TWO-STAGE PLUS PILOT PLANT
FLYASH ANALYSIS

	Mean % by wt
P_2O5	0.5
SiO_2	35.2
Fe_2O_3	6.9
Al_2O_3	17.2
TiO_2	0.7
CaO	17.4
MgO	4.3
Na_2O	1.50
K_2O	0.4
SO_3	15.3
Undetermined	0.6
Total	100.0

The marble bed of one module was converted to a spray tower several years ago for test purposes. The Two Stage Plus pilot plant was installed on the module with the spray tower (Figure 1). Flue gas was extracted from the outlet of the two stage scrubber via a duct, and treated in two horizontal CPS's in series. To insure that the slip stream was representative of the gas in the scrubber, the duct extended about 6 ft. into the 18 x 26 ft. scrubber, and pointed in a direction opposite to the gas flow. Additionally, to prevent condensation in the CPS, the inlet and outlet ducts were insulated. The amount of gas treated varied between 4800 to 8000 ACFM. Initially the gas was extracted downstream of the mist eliminator. Later tests were conducted with the gas extracted from a point ahead of the demister.

Phase 1 tests were conducted on a two field CPS that contained five gas lanes on eleven-inch centers. The collecting plate height was four feet and each field has 38 inches of treatment length. The CPS was equipped with a flat bottom and has a spray system for removing collected particles from the discharge and collecting electrode surfaces. The location of the seven banks of spray nozzles is shown in Figure 2.

Each electrical field was served by a separate transformer-rectifier set with automatic voltage controls. The spray system was operated manually with the effluent being drained back into the spray tower. Figures 3 and 4 show equipment layout for the two-field CPS.

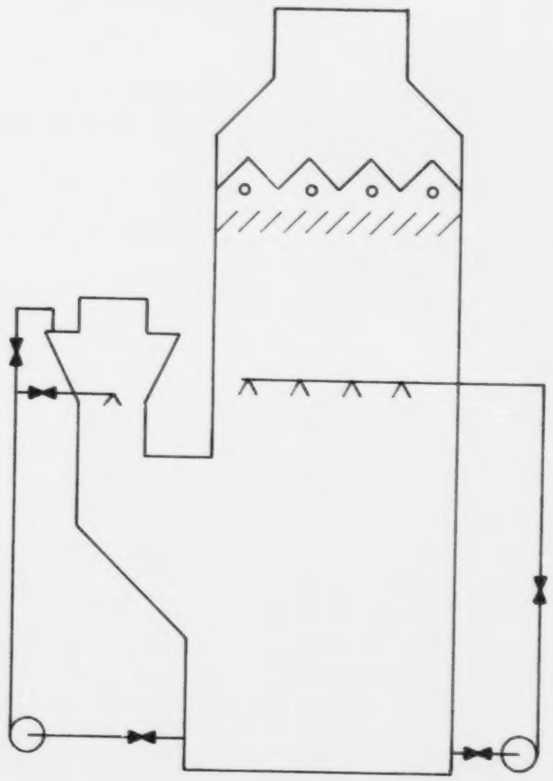

Figure 1 NSP Sherco 1

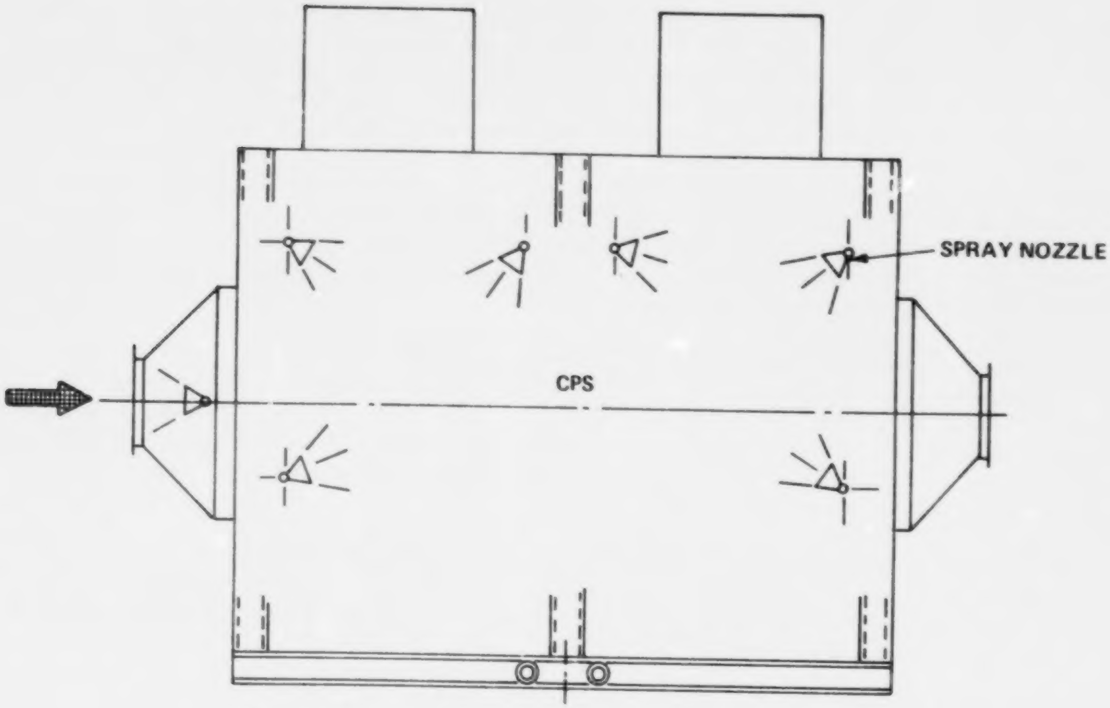

Figure 2 Spray nozzle arrangement in CPS pilot

Phase 2 tests were conducted on a five field CPS. The field height, number of gas lanes, and plate spacing were as described earlier. Treatment length and total collecting surface were 2.5 times the values used for the two field unit.

Upon leaving the CPS, the treated gas was exhausted back to the scrubber at a location downstream of the mist eliminator.

Pilot Plant Results

A total of 35 tests were conducted as part of the test program. These tests were designed to determine the particulate and SO_2 removal capability of Two Stage Plus. Immediately following these tests, several extended tests were conducted to determine the cleaning requirements of the CPS and its performance as a function of time.

Tables 3 and 4 summarize the test results of the program. The data reveals that the Two Stage scrubber is capable of removing 96% of the particulate leaving the boiler air heater outlet. This was achieved with a rod scrubber pressure drop of 5 to 6 inches w.g., a total spray liquid-to-gas ratio of 27 gallons/1000 cfm, and an average inlet particulate loading of 2.5 gr/DSCF. To be successful the CPS had to produce an emission level of 0.03 $lb/10^6$ Btu or less.

The phase 1 two-field CPS tests were performed in accordance with EPA method 5 and were each three hours long. Test runs were made at these operating conditions:

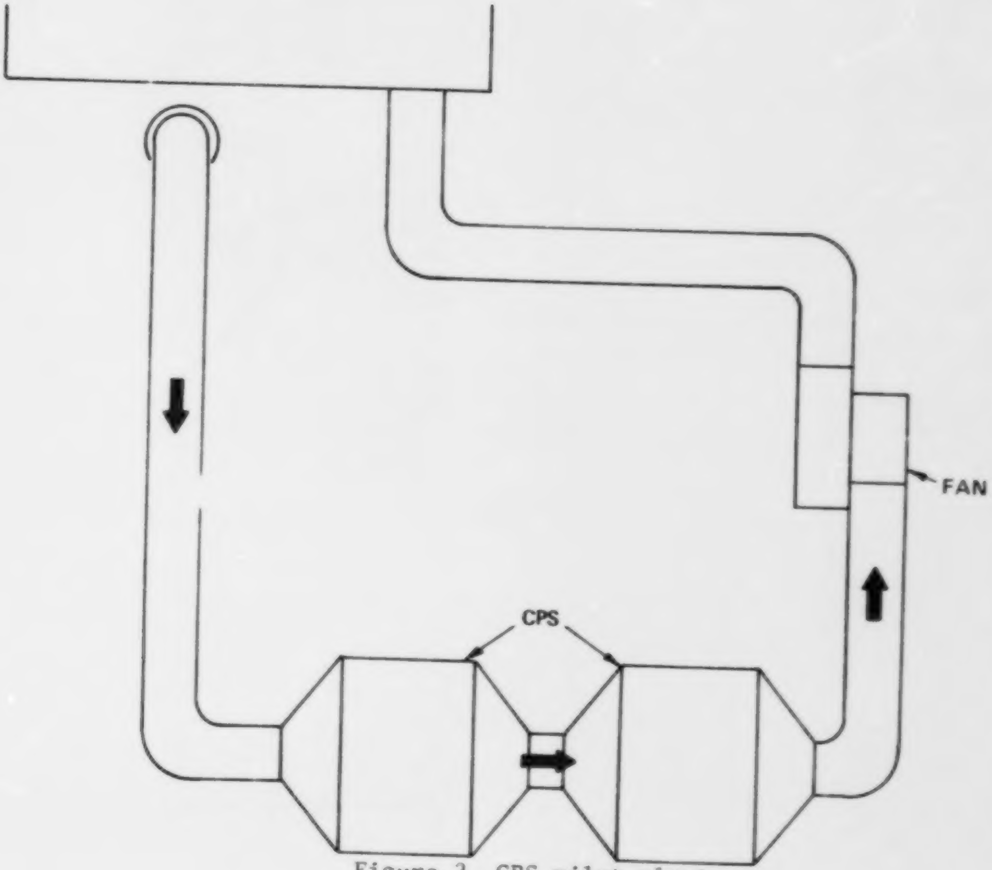

Figure 3 CPS pilot plant

(1) CPS velocity: 4, 5 & 6.5 FPS

(2) Electrical Current Density: 100% and 50%

(3) With and without On-line washing.

The results of phase 1 are shown in Table 3. During Phase 1 the scrubber gas extracted after the mist eliminator was varied. The results indicate that the CPS was capable of achieving the 0.03 lb/10^6 Btu (0.013 gr/DSCF) at a velocity of up to 4.5 ft/sec.

The results of these tests also indicated no difference in performance with or without washing. Inspection of the CPS upon completion of a three-hour test run revealed expected wetness of collecting plates and a measurable quantity of water and dust in the hopper. The majority of tests were therefore conducted without use of washing.

During the second phase of the program, the extraction point was relocated upstream of the mist eliminator, thus resulting in a higher particulate loading due to increased mist (slurry) carryover, and a five - instead of two - field CPS was used. The results of changing the extraction point reveals that the mist

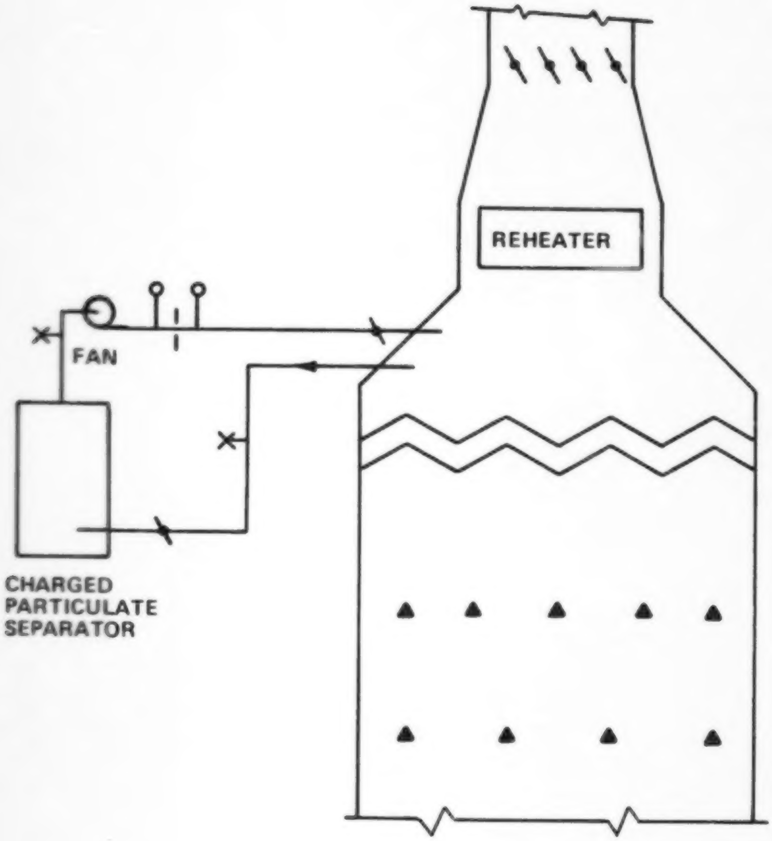

Figure 4 CPS pilot plant

eliminator is capable of removing about 60% of the solids leaving the spray tower (0.095 versus 0.035 gr/DSCF).

The phase 2 tests were conducted on a five-field CPS and the results are listed in Table 3. The data is very consistent and the 0.013 gr/DSCF (0.03 lb/106 Btu) desired emission was achieved at velocities in excess of 6.5 ft/sec. Detailed results of 20 short-term test with five fields are listed in Table 4.

The emission particulate loadings were plotted as a function of treatment time in the CPS. The graph is shown in Figure 5. The results show that 2.4 seconds of treatment time is required to meet the desired .013 gr/DSCF.

The following conclusions can be made from the pilot results:

1. On-line washing made marginal improvement on the CPS performance, when compared with no washing.

2. The effect of current density in the five-field CPS using high velocities was marginal in the 50 to 100% range.

TABLE 3 TWO STAGE PLUS CHARGED PARTICULATE SEPARATOR TEST RESULTS

Scrubber Extraction Location	Rod P (in. w.g.)	Treatment Time (sec)	Velocity (FPS)	# of Fields	Current Density %	Wash On/Off	Inlet (gr/DSCF)	Interim (gr/DSCF)	Outlet (gr/DSCF)
					Phase I				
Downstream B.E.S.	6"	1.7	3.9	2	100	Off	2.5	.03	.007
Downstream B.E.S.	6"	1.3	5.4	2	100	Off	2.5	.026	.012
Downstream B.E.S.	6"	1.1	6.15	2	100	Off	2.5	.045	.012
					Phase II				
Upstream B.E.S.	6"	1.1	6.10	2	100	Off	2.5	.093	.027
Upstream B.E.S.	6"	**3.2**	5.5	5	100	Off	2.5	.089	.008
Upstream B.E.S.	6"	2.7	6.5	5	100	Off	2.5	.100	.009
Upstream B.E.S.	6"	2.7	6.4	5	100	On	2.5	.079	.009

TABLE 4 PILOT TESTS RESULTS FOR TWO STAGE PLUS CHARGED PARTICULATE SEPARATOR

Summary of 5 Field Test Results

Velocity	Dust Load-GR/DSCF	
FPS	Inlet to CPS	Outlet from CPS
6.42	.0550	.0061
6.40	.0972	.0069
6.50	.0834	.0088
6.50	.1213	.0075
6.36	.0908	.0088
6.27	.1389	.0064
6.4	.1565	.0051
6.34	.1048	.0110
6.13	.1032	.0100
6.01	.0554	.0084
6.63	.0610	.0130
6.62	.1443	.0104
6.33	.1026	.0085
6.37	.0686	.0107
6.38*	.0998*	.0088*
5.33	.1036	.0061
5.37	.0571	.0075
5.50	.0830	.0077
5.45	.1117	.0116
5.32	.2622	.0067
5.30	.0273	.0063
5.38*	.1075*	.0077*

* Average Values

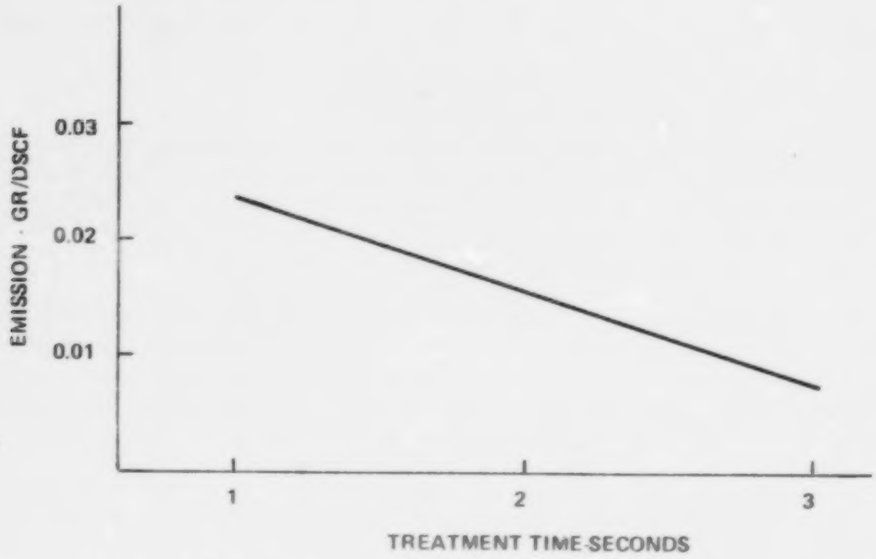

Figure 5 Pilot tests on CPS performance vs. treatment time

3. The required CPS treatment time to achieve 0.013 gr/DSCF (0.03 lb/10^6 Btu) is 2.4 seconds.

4. During the test program SO_2 levels were measured entering and leaving the Two Stage Plus. The results show a removal of 75% with an inlet concentration of 700 ppm. This is comparable with two stage scrubbing, indicating the CPS has no significant effect on SO_2 removal.

To determine any degradation in performance, a 140-hour test run on the five-field pilot CPS was conducted. Emission was checked periodically during the week using EPA method 5. A portable opacity monitor was installed downstream of the CPS to yield a continuous surveillance of the operation. Figure 6 is a bar chart indicating test and cleaning cycles for this long-term performance test. Four tests conducted during this period showed consistent CPS performance. The outlet particulate loading did not exceed 0.01 gr/DSCF. A minimal amount of washing (six) was required during this period with each cycle lasting 10 minutes only.

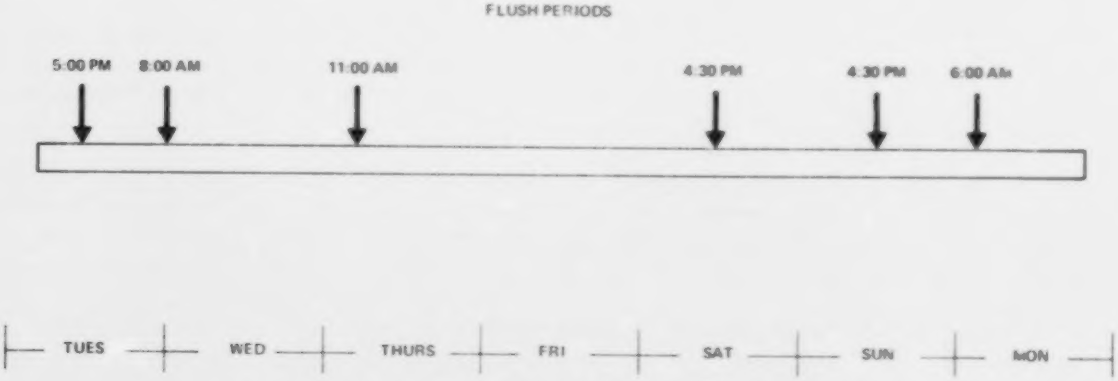

Figure 6 CPS pilot long-term performance test

CONCEPTUAL DESIGN

Design Criteria

The full size unit selected for the conceptual design application is a 500-MW unit. The fuel fired is a Western coal with about 8000 Btu/lb heating value, and two levels of sulfur, 0.54 and 2.3%. The design requires 70 and 90% SO_2 removal for respective sulfur levels and an outlet particulate emission of 0.03 lb/10^6 Btu (0.013 gr/DSCF).

The rod scrubber/spray tower design selected for this application requires a liquid-to-gas ratio of 85 gpm/1000 cfm. The pressure drop across the rod scrubber has been set at 4 in. w.g. The CPS gas treatment time used in this design assumes 3.13 seconds, which is 30% higher than the pilot value of 2.4 seconds.

An intermittent wash system to operate off or on-line is required to keep the CPS clean. The wash system frequency of operation will be in the order of once per day.

The material selection for the Two Stage Plus is based on C-E's experience with two stage scrubbers, charged particulate separators, and the pilot plant at Sherburne County. Material evaluation over the years has led to improvements, especially in the high wear components, such as rod scrubbers, piping, and pumps. In addition, the CPS experience in Belgium provided telling testimony on the use of Type 316L stainless steel, where it has shown little wear in the last 15 years. Type 316L ss is the material for the scrubber shell and electrodes, refractory the material for the rods, fiberglass for the piping, and rubber lining for the pumps. For C-E experience with 316L ss in flue gas scrubbers, see Lewis et. al. (1978).[6]

Description

The conceptual design is shown isometrically in Figure 7. The Two Stage Plus consists of 5 modules including a spare. The gas flow entering each module is approximately 450,000 cfm.

In the rod section, the vertical spacing between the rods is automatically controlled to maintain 4 inches w.g. of pressure drop. The rod scrubber, not only removes most of the particulate matter from the flue gas, but also a portion of the SO_2 in the flue gas. A steam soot blower located in the inlet duct prevents deposit from building on the wet/dry interface. The spray slurry in the rod scrubber discharges into the reaction tank. Figure 8 shows a flow schematic of the Two Stage Plus.

From the rod scrubber, the flue gas turns 180 degrees and enters the second stage consisting of a spray tower. The spray tower is a low pressure drop SO_2 absorber. In the spray tower the spray slurry is sprayed counter-current to the gas. The spent spray tower slurry is also discharged into the reaction tank.

The flue gas then passes through a bulk entrainment separator (BES). The BES consists of vanes mounted at 45-degree angles on 3-inch parallel spacing. The BES is maintained in a clean state by intermittent washing with a fixed grid arrangement.

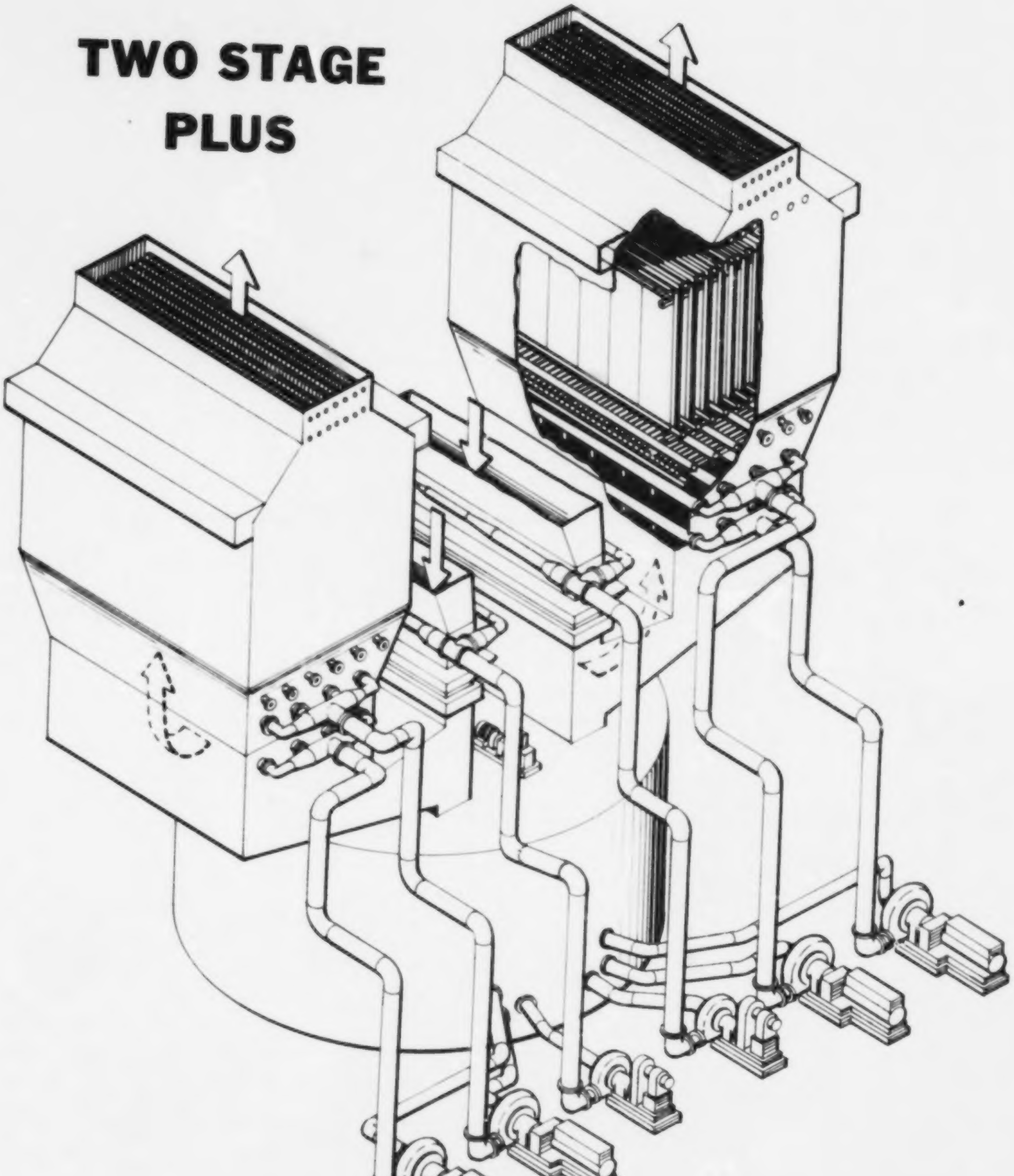

Figure 7 Isometric cutaway of Two Stage Plus

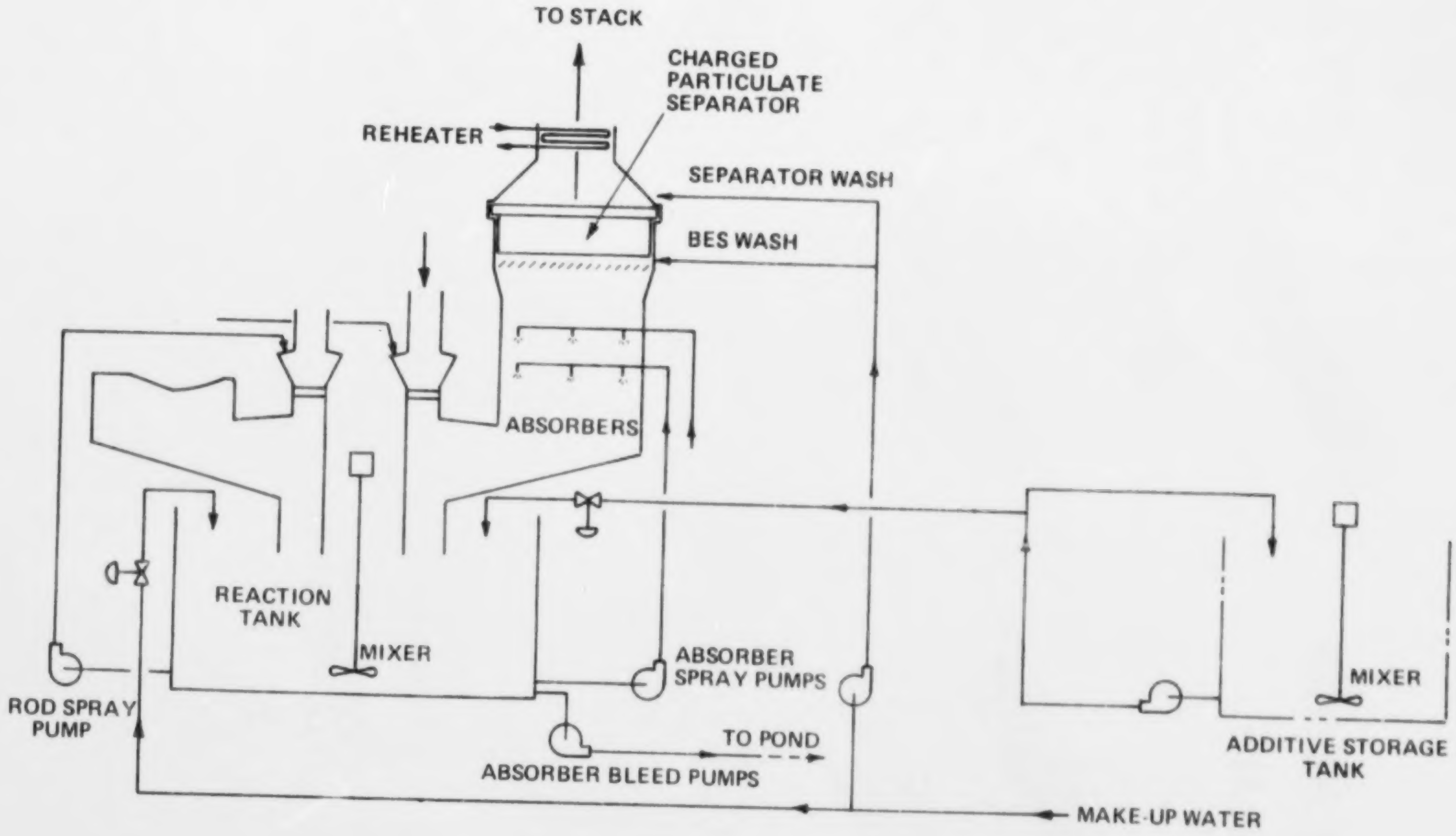

Figure 8 Two Stage Plus flow schematic

Upon leaving the BES, the gas enters the charged particulate separator, where liquid entrainment and particulate matter are further reduced. The CPS is a vertical compartment containing a grid of electrical cells. These cells are comprised of 316L stainless steel discharge and collecting electrodes. To facilitate the particulate removal, the gas is allowed to travel at a reduced velocity through the CPS. The collector plates will be cleaned periodically using a fixed grid flush system.

The CPS is divided into two cells powered with a transformer rectifier. Insulator compartments external to the CPS shell span two opposite sides of the shell. The discharge electrode wire frames extend below the collecting plates and are connected to give greater stability to the high voltage system.

Upon leaving the CPS, the gas temperature is increased by 30 F to eliminate the plume and to bring the gas above its dewpoint.

The auxiliary equipment, which includes the reaction tank, bleed, additive feed, and makeup water, will not be described in this paper. Instead, the reader is referred to a paper presented by Martin (1977).[6]

Economic Evaluation

The capital and operating costs for the full scale Two Stage Plus are shown in Table 5. Four cases were evaluated for two sulfur levels, 2.3 and 0.54%, with and without taking credit for the alkalinity in the ash. These specific variables were selected in order to facilitate comparison with competing concepts.

The capital costs were based on 1981 dollars (present worth) for 35 years. The installed capital cost includes, the scrubbing system, steel, building, electrical, controls, etc. The Two Stage Plus installed cost for a 500-MW unit increases by 10% as the sulfur in the coal increases from 0.54% to 2.3%. This is primarily due to the increase in pumping capacity. The presence of calcium in the ash reduces the installed cost slightly primarily due to a reduction in the additive subsystem.

The operating cost has been evaluated based on a 35 year life, load factor of 75%, and present worth dollars. Unlike the installation cost the operating cost is significantly higher for the higher sulfur coal. The cost is further increased when the alkalinity in the ash is ignored.

The economic data for the Two Stage Plus design is of even more interest when compared against other FGD concepts. Table 5 also shows a comparison of the costs for four FGD concepts, 3 wet scrubbing and 1 dry scrubbing. The wet scrubbers include the Two Stage Plus, the Two Stage, and the ESP/Spray Tower. The dry scrubbing data is based on information presented by Basin Electric at the EPA Scrubber Symposium in March 1979. For the high sulfur condition the stoichiometric lime feed rate was assumed to be 160% based on SO_2 removal. The manpower requirement was also adjusted to allow for the dry system.

In evaluating the four concepts, the following assumptions were made:

TABLE 5 ECONOMIC EVALUATION WITH CREDIT FOR ALKALINITY IN FLYASH

BASIS: 500 MW UNIT
2.3% SULFUR IN COAL

	TWO-STAGE Cost*/Basis $	TWO-STAGE PLUS Cost*/Basis $	ESP/SPRAY TOWER Cost*/Basis $	DRY SCRUBBER/BAG FILTER Cost*/Basis $
Capital	39.0 X 10^6/Actual	43.0 X 10^6/Actual	60.0 X 10^6/Actual	50.0 X 10^6/Actual
Additive	24.7 X 10^6/95,200 tons/yr. $CaCO_3$	24.7 X 10^6/95,200 tons/yr. $CaCO_3$	47.0 X 10^6/181,000 tons/yr. $CaCO_3$	196.8 X 10^6/147,000 tons/hr CaO
Power	51.3 X 10^6/22,000 KW	39.0 X 10^6/16,500 KW	44.0 X 10^6/19,000 KW	21.0 X 10^6/9,100 KW
Reheat	20.0 X 10^6/71.4 mm BTU/hr	20.0 X 10^6/71.4 mm BTU/hr	20.0 X 10^6/71.4 mm BTU/hr	0/-
Manpower	32.8 X 10^6/10 oper. 12 maint.	34.2 X 10^6/10 oper. 13 maint.	34.2 X 10^6/10 oper. 13 maint.	26.8 X 10^6/10 oper. 8 maint.
Replacement	26.8 X 10^6/Actual	29.8 X 10^6/Actual	29.8 X 10^6/Actual	18.0 X 10^6/bag filter, atomizers, bearings, etc.
Total	194.6 X 10^6	196.7 X 10^6	235.0 X 10^6	312.0 X 10^6

* Cost is based on 35 year life, 75% load factor, and 1981 worth, with commercial date set at 1981.

TABLE 5 CONT'D ECONOMIC EVALUATION WITH NO CREDIT FOR ALKALINITY IN FLYASH

BASIS: 500 MW UNIT
2.3% SULFUR IN COAL

	TWO STAGE	TWO STAGE PLUS	ESP/SPRAY TOWER	DRY SCRUBBER/BAG FILTER
	Cost*/Basis $	Cost/Basis $	Cost/Basis $	Cost/Actual $
Capital	40.0 X 10^6/Actual	44.0 X 10^6/Actual	60 X 10^6/Actual	50 X 10^6/Actual
Additive	47.0 X 10^6/181,000 tons/yr. $CaCO_3$	47 X 10^6/181,000 tons/yr $CaCO_3$	47 X 10^6/181,000 tons/yr $CaCO_3$	196.8 X 10^6/147,000 tons/yr CaO
Power	51.3 X 10^6/22,000 KW	39 X 10^6/16,800 KW	44 X 10^6/19,000 KW	21.0 X 10^6/9,100 KW
Reheat	20.0 X 10^6/71.4 mm BTU/hr	20.0 X 10^6/71.4 mm BTU/hr	20.0 X 10^6/71.4 mm BTU/hr	0/-
Manpower	32.8 X 10^6/10 oper. 12 maint.	34.2 X 10^6/10 oper. 13 maint.	34.2 X 10^6/10 oper. 13 maint.	26.8 X 10^6/10 oper. 8 maint.
Replacement	26.8 X 10^6/Actual	29.8 X 10^6/Actual	29.8 X 10^6/Actual	18.0 X 10^6/bag filters, atomizers, bearings, etc.
Total	217.9 X 10^6	214.0 X 10^6	235.0 X 10^6	312.0 X 10^6

* Cost is based on 35 year life, 75% load factor, and 1981 worth, with commercial date set at 1981.

TABLE 5 CONT'D ECONOMIC EVALUATION WITH CREDIT FOR ALKALINITY IN FLYASH

BASIS: 500 MW UNIT
0.54% SULFUR IN COAL

	TWO-STAGE	TWO-STAGE PLUS	ESP/SPRAY TOWER	DRY SCRUBBER/BAG FILTER
	Cost*/Basis \$	Cost*/Basis \$	Cost*/Basis \$	Cost*/Basis \$
Capital	34.0 X 10^6/Actual	39.0 X 10^6/Actual	54.0 X 10^6/Actual	50.0 X 10^6/Actual
Additive	0/-	0/-	8.5 X 10^6/42,500 tons/yr. $CaCO_3$	26.8 X 10^6/25,800 tons/yr CaO
Power	45.0 X 10^6/19,300 KW	32.8 X 10^6/14,000 KW	37.8 X 10^6/16,200 KW	20.0 X 10^6/8,700 KW
Reheat	20.0 X 10^6/71.4 mm BTU/hr	20.0 X 10^6/71.4 mm BTU/hr	20.0 X 10^6/71.4 mm BTU/hr	0/-
Manpower	32.8 X 10^6/10 oper. 12 maint.	34.2 X 10^6/10 oper. 13 maint.	34.2 X 10^6/10 oper. 13 maint.	26.8 X 10^6/10 oper. 8 maint.
Replacement	26.8 X 10^6/Actual	29.8 X 10^6/Actual	29.8 X 10^6/Actual	18.0 X 10^6/bag filters, atomizers bearings, etc.
Total	158.6 X 10^6	155.8 X 10^6	184.3 X 10^6	141.9 X 10^6

* Cost is based on 35 years life, 75% load factor, and 1981 worth, with commercial date set at 1981.

TABLE 5 CONT'D ECONOMIC EVALUATION WITH NO CREDIT FOR ALKALINITY IN FLYASH

BASIS: 500 MW UNIT
.54% SULFUR IN COAL

	TWO-STAGE	TWO-STAGE PLUS	ESP/SPRAY TOWER	DRY SCRUBBER/BAG FILTER
	Cost*/Basis $	Cost*/Basis $	Cost*/Basis $	Cost*/Basis $
Capital	35.0 X 10^6/Actual	40.0 X 10^6/Actual	54.0 X 10^6/Actual	50.0 X 10^6/Actual
Additive	8.50 X 10^6/42,500 tons/yr $CaCO_3$	8.5 X 10^6/42,500 tons/yr. $CaCO_3$	8.5 X 10^6/42,500 tons/yr $CaCO_3$	26.8 X 10^6/25,800 tons/yr. CaO
Power	45 X 10^6/19,300 KW	32.8 X 10^6/14,000 KW	37.8 X 10^6/16,000 KW	20.0 X 10^6/8,700 KW
Reheat	20.0 X 10^6/71.4 mm BTU/hr	20.0 X 10^6/71.4 mm BTU/hr	20.0 X 10^6/71.4 mm BTU/hr	0/-
Manpower	32.8 X 10^6/10 oper. 12 maint.	34.2 X 10^6/10 oper. 13 maint.	34.2 X 10^6/10 oper. 13 maint.	26.8 X 10^6/10 oper. 8 maint.
Replacement	26.8 X 10^6/Actual	29.8 X 10^6/Actual	29.8 X 10^6/Actual	18.0 X 10^6/bag filters, atomizers, bearings, etc.
Total	168.1 X 10^6	165.3 X 10^6	184.3 X 10^6	141.9 X 10^6

* Cost is based on 35 year life, 75% load factor, and 1981 worth, with commercial date at 1981.

1) Limestone stoichiometry for the wet scrubbers of 110% based on the SO_2 removal.

2) Credit for calcium in the ash was taken only for the wet concepts.

3) 75% load factor.

4) 35 year plant life with 8% escalation and 9% discount rates. Start-up date set at 1981.

5) Limestone cost as of 1981: \$8.7/ton. Lime cost as of 1981: \$45/ton.

6) Steam cost set at \$2.0/10^6 Btu in 1981.

7) Power cost set at \$.013/kWh (1981).

8) Operator cost/year = \$50,000

The cost breakdown shows that additive feed, power and reheat are the determining factors in evaluating the four concepts. As the sulfur in the coal increases, the differential in power and reheat costs between the dry and the wet concepts remains relatively constant, but the additive cost differential becomes extremely high.

A plot of evaluated cost versus the % sulfur in the coal is shown in Figures 9 and 10. The graph shows that among the wet concepts the Two Stage Plus has the least evaluated cost. When compared with dry scrubbing the Two Stage Plus is slightly more costly at the 0.54% sulfur level, but at the 2.3% sulfur level, the Two Stage Plus is significantly less. The Two Stage Plus appears to be economical above 0.7% sulfur in the coal if credit for the alkalinity in the flyash is considered, and above 0.8% if the ash alkalinity is ignored.

CONCLUSION

The Two Stage Plus is technically and economically viable as an SO_2 and particulate control system. Its ability to meet the new EPA requirements can be predicted safely.

In terms of cost, Two Stage Plus is the most economical of the majority of the wet scrubbing concepts. When compared with the dry system, Two Stage Plus is economical if the sulfur in the coal exceeds 0.8%. When the coal's ash has high alkaline quantities, as do many western subituminous and lignite coals, the breakpoint is even lower, i.e. (0.7% Sulfur).

For Western fuel-fired plants, with highly alkaline flyash that is difficult to collect in precipitators, Two Stage Plus looks very promising.

ACKNOWLEDGMENT

Special appreciation is given for the assistance provided by Northern States Power Company's management and plant personnel during the test program.

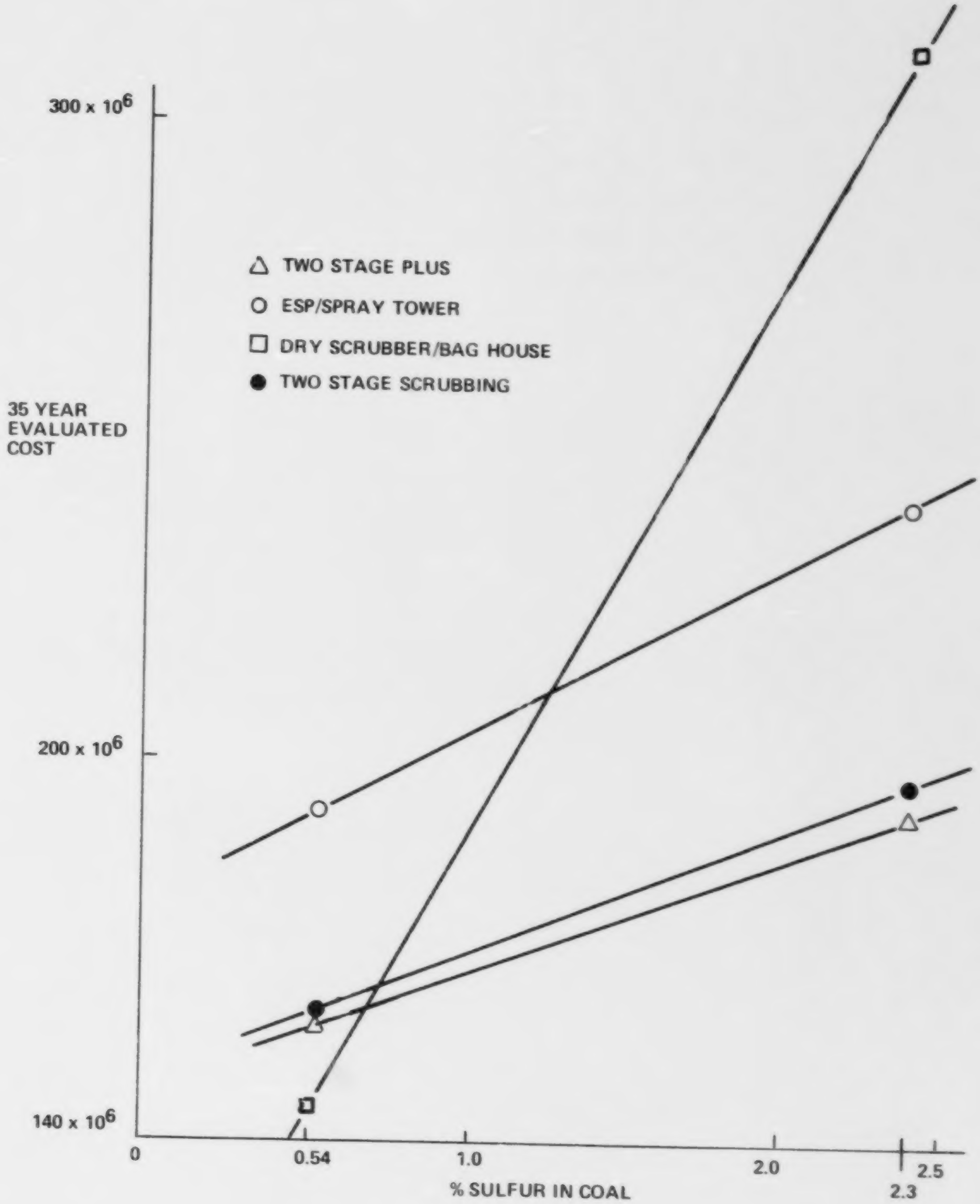

Figure 9 35-year evaluated cost as a function of sulfur in coal with credit for alkalinity in flyash

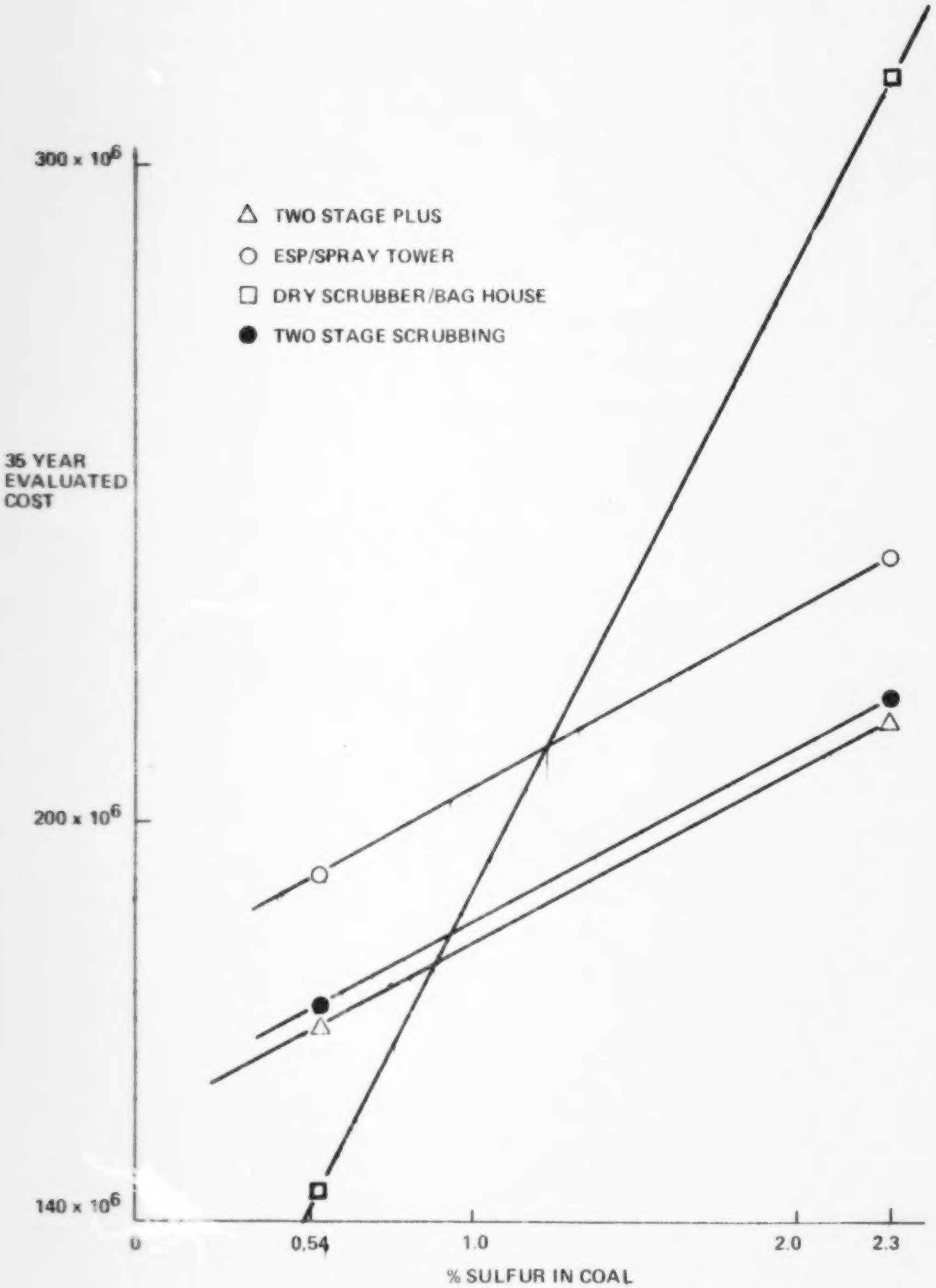

Figure 10 35-year evaluated cost as a function of sulfur in coal with no credit for flyash alkalinity

REFERENCES

1. 36 Federal Register, page 24876, December 23, 1971.

2. Kruger, R. J. Experience with Limestone Scrubbing At Sherburne County Generating Plant, Northern States Power Co., (Presented at EPA Symposium on Flue Gas Desulfurization, Hollywood, Florida, November 1977).

3. Green, K. and Martin, J. R., Conversion of the Lawrence #4 Flue Gas Desulfurization Systems. (Presented at EPA Symposium on Flue Gas Desulfurization, Hollywood, Florida, November 1977).

4. Green, K., Conrad, L., Martin, J. R., and Kingston, W. H. Commitment to Air Quality Control. In: Proceedings of the American Power Conference, Haigh, B. (ed). Chicago, American Power Conference, 1978. p. 632-645

5. Van Ness, R. P., Kingston, W. H., and Borsare, D. C. Operation of C-E Flue Gas Desulfurization System for High Sulfur Coal at Louisville Gas & Electric Company, Cane Run #5. (Presented at American Power Conference, Chicago, Illinois, April 23-25, 1979).

6. Kettner, D. C., Hickok, W. W., Martin, J. R., and Dutton, R. W. Design of a Spray Tower Scrubber For Coal Creek Station. (Paper presented at PACHEC '77 - The Second Pacific Area Chemical Engineering Conference, Denver, Col., August 28-31, 1977).

7. Lewis, E. C., Stengel, M. P., and Maurin, P. G. Performance of Type 316L Stainless Steel and other Materials in Electric Utility Flue Gas Wet Scrubbers (Paper presented at APCA, IGCI and NACE Seminar on Corrosion in Air Pollution Control Equipment, Atlanta, GA, January 17-19, 1978). Combustion Engineering Publication TIS-5366.

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